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**FIELD MEASUREMENT AND MODEL EVALUATION
PROGRAM FOR ASSESSMENT OF THE ENVIRONMENTAL
EFFECTS OF MILITARY SMOKES**

**ANALYSIS METHODS AND RESULTS OF HEXACHLOROETHANE
SMOKE DISPERSION EXPERIMENTS CONDUCTED AS PART OF
ATTERBURY-87 FIELD STUDIES**

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The results of five dispersion experiments conducted using hexachloroethane (HC) smoke pots are described. The experiments included (a) measurement of time-dependent release rate (4 trials) and exit temperature (1 trial), (b) measurement of meteorological variables using a 10-m instrument tower and a 2-m mast upwind of the smoke source, (c) sampling of the particulate phase at four heights (2, 4, 6 and 8 m) on 46 sampling masts organized into four transects located between 60 and 500 m from the source, (d) twelve samples of the vapor phase which were chemically analyzed for four specific organic compounds and (e) determination of the particle size distribution at a single location using a quartz-crystal-microbalance cascade impactor. Chemical analysis methods for the particulate and vapor phases are described. All particulate samples were analyzed for zinc and aluminum; 10 of the most heavily exposed filters were analyzed for 45 elements using a combination of inductively coupled argon-plasma, atomic-emission spectroscopy (40 elements) and ion chromatography (5 elements). Twenty-two additional samples were analyzed for 11 elements. A gas chromatography method used to analyze the vapor samples is also described. The results of the study include (a) information on the approximate composition of the HC smoke particulate and vapor phases, (b) determination of the HC smoke particle size distribution and (c) concentration data with accompanying meteorological and source information which are suitable for testing and improving atmospheric dispersion models. <i>Reviewed</i>			
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EXECUTIVE SUMMARY

This report describes the results of five dispersion experiments carried out using hexachloroethane (HC) smoke pots. The objectives of these experiments, which are part of the Atterbury-87 Field Study, were (a) to characterize the HC smoke in physical and chemical terms and (b) to obtain dispersion data from which to validate and improve atmospheric dispersion models. A companion report by Liljegren et al. (1989) describes the Atterbury-87 Field Study in detail; this report focuses on (a) the methods used to analyze the HC smoke samples chemically, (b) the physical and chemical nature of the HC smoke as determined under the field test conditions and (c) the HC smoke concentration data which will be used as part of a larger model evaluation and improvement program.

The five HC-smoke dispersion experiments were conducted under daytime convective conditions in moderately flat terrain at Camp Atterbury, Indiana during November, 1987. The source for each test consisted of 18-20 M5 hexachloroethane (HC) smoke pots burned over a period of between 25 and 47 min. The plume was mapped using 46 sampling masts organized into four transects at distances from 50 to 675 m from the source. The particulate phase of the smoke was collected at four heights (2, 4, 6 and 8 m) on each mast using cellulose-ester membrane filters housed in aspirated cassettes. In addition, twelve samples of the vapor phase were collected using Tenax-filled tubes in series with filter cassettes. Particle size was measured at a single location using a quartz-crystal-microbalance cascade impactor. Meteorological data were collected using a 10-m instrument tower and a 2-m mast upwind of the source.

The filter samples were analyzed by inductively coupled argon-plasma atomic-emission spectrometry and ion chromatography. All 920 samples collected during the five tests were analyzed for zinc and aluminum. Ten of the most heavily exposed filters were analyzed for 45 elements and 22 additional samples were analyzed for 11 elements. The vapor-phase samples were analyzed for four specific chlorinated organic compounds.

Results indicated that the HC smoke has a bimodal particle size distribution with about 5 - 15% of the mass contained in the smaller size range. The chemical analysis of the samples revealed that the smoke is roughly 90% particulate and 10% vapor by mass. The particulate phase contains zinc, chlorine, aluminum, iron and lead in significant quantities. The four targeted organic compounds were found to account for about a third of vapor phase. The concentration data compared favorably with other

dispersion data when presented in a nondimensional form which scales out the effects of source strength and local ambient conditions, despite the fact that these data were corrected to account for the effect of filter loading.

A key point to be stressed is the variability of smoke composition. This variability, seen in all aspects of the chemical analysis, indicates that individual smoke samples may differ greatly from the mean determined in our study. Moreover, factors such as ambient temperature, ambient humidity, wind speed and pot orientation may all affect the HC smoke products although the examination of these effects is beyond the scope of the present study.

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NOMENCLATURE

<u>Symbol</u>	<u>Meaning</u>
C	Concentration
C_y	Crosswind-integrated concentration
d_g	Geometric mean particle size
HC	Hexachloroethane
L	Monin-Obukov length scale
m	Mass
m_c	Characteristic constant of membrane filters; defines exponential decrease in ϵ for m_{zn} values above m_o
m_o	Characteristic constant of membrane filters; $\epsilon = 1$ when the $m_{zn} \leq m_o$
n	Exponent of vertical wind speed profile; determined by fitting vertical profile data to power law form $u = a z^n$
RH	Relative humidity
T	Temperature
ΔT	Temperature difference
t	Time
u	Component of wind velocity lying in the direction of the mean wind
$\overline{u}$	Mean wind speed
u_*	Friction velocity
$\dot{V}$	Volumetric flow rate
$\dot{V}_o$	Nominal volumetric flow rate
v	Horizontal component of the wind velocity perpendicular to the mean wind
w	Vertical component of the wind velocity
w_*	Convective velocity scale
x	Local coordinate used to specific locations within sampling grid; the positive x coordinate axis points east
y	Local coordinate used to specify locations within the sampling grid; the positive y coordinate axis points north
z	Height above ground
z_i	Height of convective boundary layer; inversion height
z_o	Roughness height

ϵ	Collection efficiency
ϕ	Inclination of wind velocity; mean or instantaneous depending on context
θ	Mean wind direction; also used to denote instantaneous wind azimuth
σ	Denotes a standard deviation; subscript specifies variable of interest
σ_g	Geometric standard deviation
σ_y	Lateral standard deviation of concentration profile; also referred to as plume width

1. INTRODUCTION

As part of a program to characterize military smokes under actual field conditions, nine smoke dispersion experiments were conducted at Camp Atterbury, Indiana during November, 1987. Four of these nine experiments were carried out using a fog-oil smoke generator as the source; the remaining five tests were carried out using hexachloroethane (HC) smoke pots. This series of field experiments is referred to collectively as the Atterbury-87 Field Studies.

The Atterbury-87 Field Studies are described in detail in a companion report by Liljegren et al. (1989). This document summarizes the results of the HC smoke trials and provides additional information on the physical and chemical characteristics of the HC smoke. Brief summaries of the relevant material from the companion report are provided to aid in understanding and interpreting the results presented herein.

2. FIELD STUDY

2.1 Test Site and Sampling Grid

The Camp Atterbury test site and sampling grid are shown in Fig. 1. The test area is a large grassy meadow surrounded on roughly three sides by hills 25 to 50 m high. The test area itself is relatively flat with a moderate downward slope of between 1 and 2% from northwest to southeast. The ground cover during the period of the study was roughly 1 m high and fairly uniform across the test area, although somewhat taller bushes and a few isolated trees were also present. The area surrounding the site is densely forested in all directions with deciduous trees 10 to 20 m tall. The terrain and vegetation features of the surroundings undoubtedly affect the structure of the wind field, although the flat terrain and regular ground cover within the test area itself should give a nearly uniform flow.

To orient the sampling grid at Camp Atterbury, we analyzed the meteorological data records for 1985 and 1986 from the National Weather Service recording station at Indianapolis, Indiana, 60 miles north of the site. This analysis indicated that the wind is predominantly from the southwest in November. In addition, we logged wind and temperature data near the proposed test area using two portable instrument stations shortly before full-scale operations at the site began. These data confirmed the predominant southwesterly direction of the wind in the daytime.

Based on the results of our analysis, a line of alternative source locations was established in the southwest corner of the test area and sampling transects

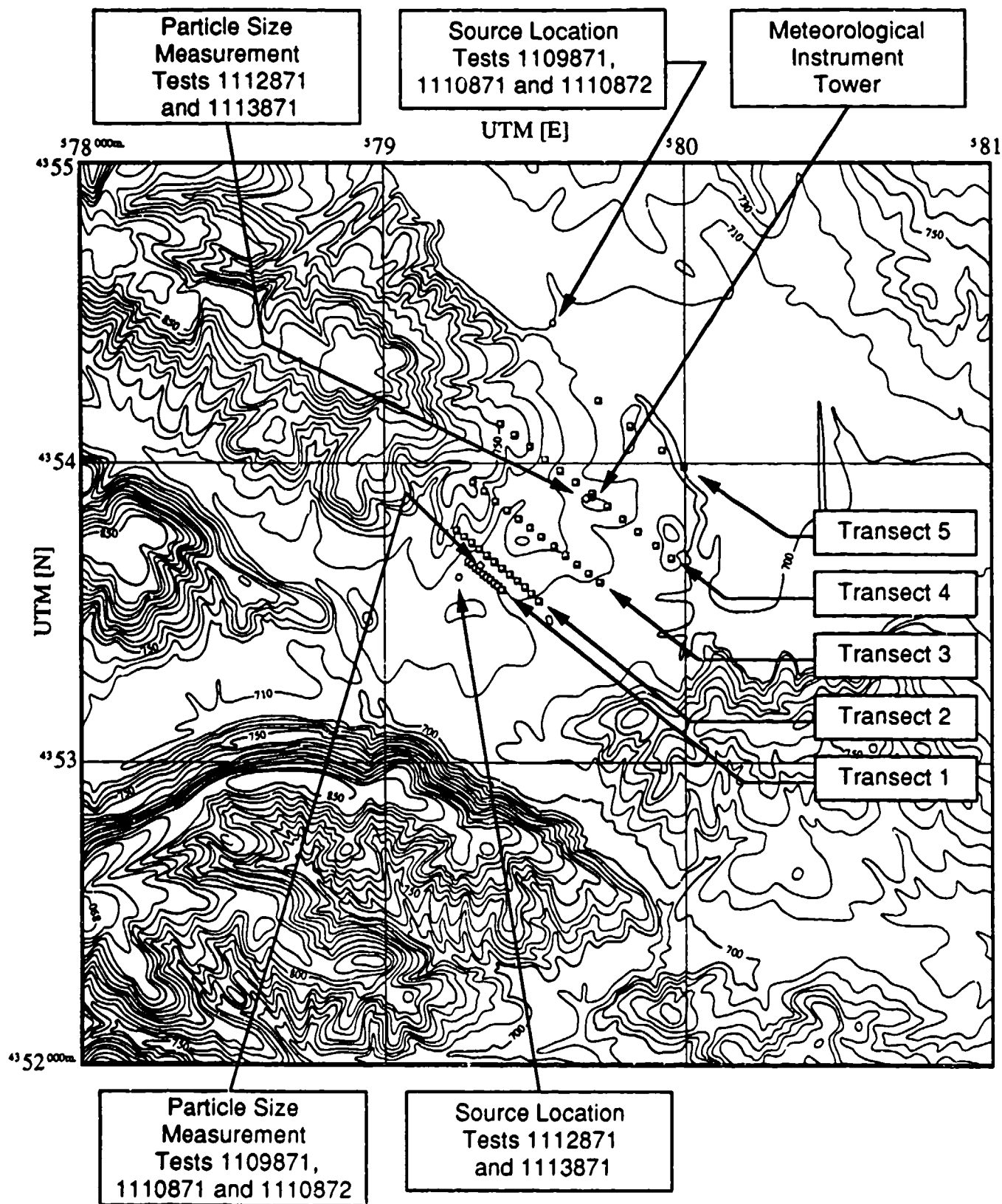


Figure 1. Topographical map of the Camp Atterbury Test Site. North and east universal transverse meridian (UTM) coordinates are given in meters. Elevations are given in feet above sea level with contours representing 10-ft increments. Topographical information is based on the United States Geological Survey map of Nineveh, Indiana. Test designations consist of the date the test was conducted followed by the number of the test on that date.

(designated Transects 1 through 5) were laid out perpendicular to the predominant wind direction at distances roughly 50, 100, 250, 450 and 675 m from this line. With the exception of Transect 5 which consisted of only four sampling masts and which was not used in any of the HC trials for logistical reasons, each transect subtended an arc of at least 90° with respect to the possible source locations.

Figure 2 isolates the sampling grid and illustrates the local coordinate system used to specify the source and sampler locations. Here, the mean wind direction for each of the five tests is shown. Each test is identified by a seven-digit code consisting of the date on which the test was conducted in the form MMDDYY followed by a single digit (1 or 2) indicating the number of the test on that particular day. As shown, the wind was out of the southwest as anticipated for two of the five HC trials (Tests 1112871 and 1113871). For the remaining three trials (Tests 1109871, 1110871 and 1110872), the wind was out of the north-northeast as the result of a storm front passing through the area. Fortunately, we were able to conduct tests during this period by locating the source northeast of the sampling grid as shown in Fig. 2.

Detailed coordinate information for the grid is given in Appendix A.

2.2 HC Smoke Source

2.2.1 Physical Characteristics

The ABC-M5 30-lb HC smoke pot produces a dense gray-white smoke as a result of the exothermic reaction between a mixture of zinc oxide, aluminum metal and hexachloroethane. The chemical reaction produces primarily zinc chloride particles which are believed to collect water from the atmosphere to form the aerosol droplets which ultimately constitute the smoke. It is reported that about 70 to 80% of the original pot mass is released as smoke, the remainder being distributed among a variety of end-products one of which is a black, wet material deposited in the immediate vicinity of the pot. This material dries and hardens over time. It is virtually impossible to remove the harden material from the surfaces on which it deposits.

A total of 100 HC pots were acquired for the study and stored in an ammunition bunker at the Atterbury Reserve Forces Training Center prior to use. Physically, the M5 smoke pot consists of a cylindrical canister 0.215 m in diameter and 0.24 m high filled with approximately 13.6 kg of reagent. The canister is rounded slightly at the bottom edge to facilitate stacking and is covered by a circular tear strip which was removed and discarded before use. A plastic cup containing a starter mixture is embed-

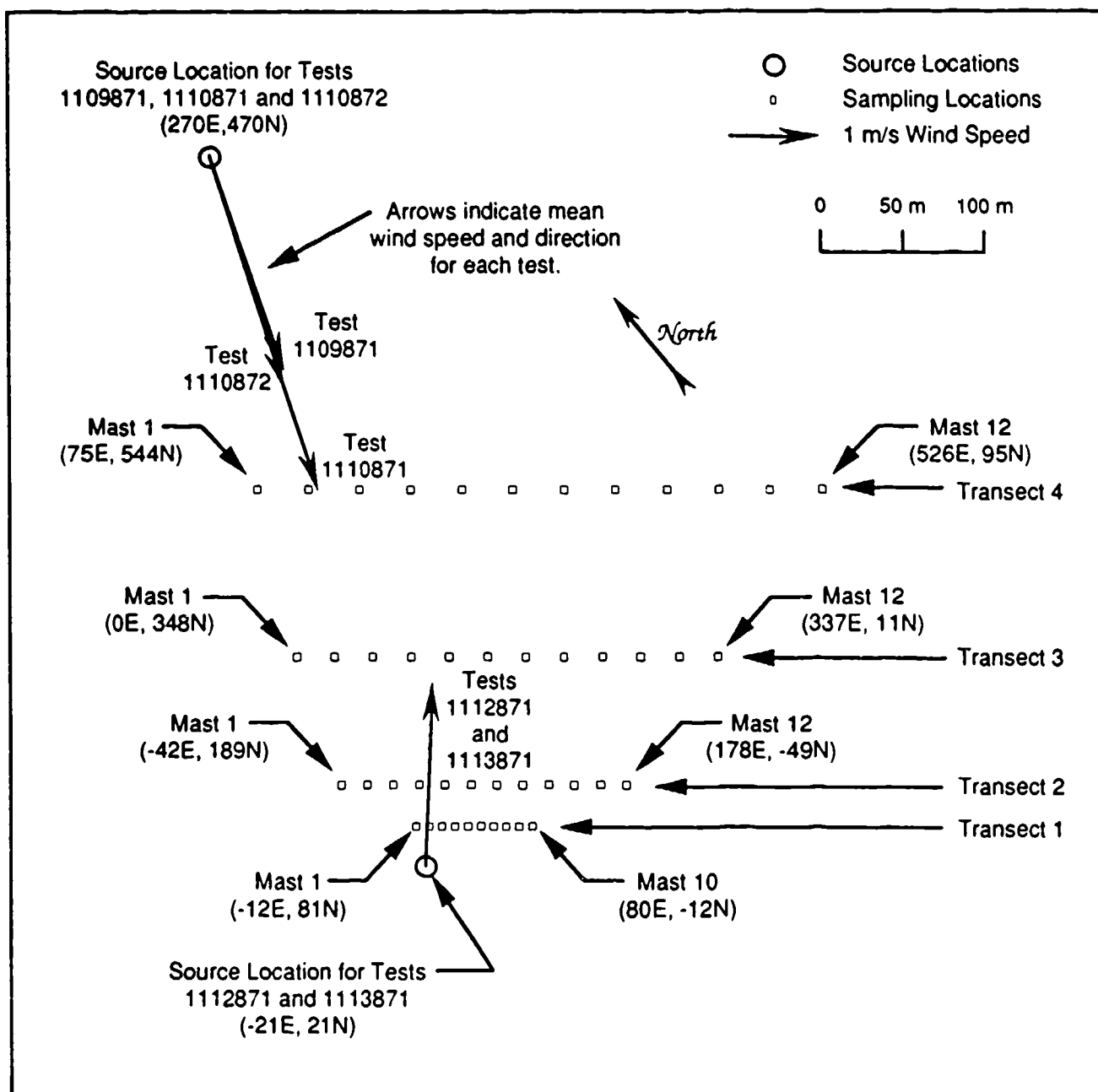


Figure 2. Sampling grid used for the Atterbury-87 HC smoke dispersion trials. Coordinates are given in meters relative to a local origin. The wind vectors shown represent averages over the period of each test.

ded in the top of the charge. An electric squib provided with the pot was employed to ignite the material in our tests.

A single pot from our inventory was used initially to familiarize ourselves with the proper handling procedures and to determine the approximate burn time. In order to achieve statistically significant results in the dispersion experiments, the duration of the release must be several times greater than the Lagrangian time scale of the convective motions, a value typically between 1 and 5 minutes. On the other hand, the test should not be so long as to be influenced by the diurnal and mesoscale changes in the atmospheric boundary layer. Based on the observed burn time of 18 minutes and a desired release time of approximately an hour, we decided to execute four burns in succession. Moreover, we estimated that it was necessary to burn five pots simultaneously to ensure that most of the filter samples would fall within the range of chemical analysis equipment. Thus, our basic test plan called for burning 20 pots in four sets of five each. A total of 5 tests were therefore possible.

In order to measure the mass of smoke material released, we placed the pots on a fireproof masonry board overlaid on a wooden pallet. The pallet was placed on a 1000-lb capacity scale which rested directly on the ground. In the first full-scale release (Test 1109871), we placed 19 pots side by side on the masonry board with the intention of remotely igniting the pots successively in four groups. However, the intense heat of the burning pots quickly ignited all the others and the entire test lasted only 25 min. To provide a more controlled ignition, the remaining tests were all carried out by stacking the pots. It was hoped that, as each pot burned down, the one below it would be ignited and a more or less steady release rate would be achieved. During the next release (Test 1110871), the stacks collapsed into a pile about midway through the test, and, once again, the remaining pots were ignited prematurely. We then decided to bind the pots together with wire fencing. Controlled ignition was finally achieved using this method, although the release rate increased noticeably as each successively lower pot ignited. This increase was caused by the more rapidly burning starter mixture located in the top of each pot. The last three tests were conducted in this manner, and all gave fairly consistent burn times and release rates. Two pots were withheld from the final full-scale test (Test 1113871) in order to study the difference in burn characteristics between a pot in the normal upright position and one lying on its side. The source configuration used in each of the five full-scale trials is summarized in Table 1.

Besides measuring the mass of the pots, an attempt was made during one of the tests (Test 112871) to determine the initial smoke temperature using a 24-gauge

Table 1. Summary of source configurations used for HC smoke trials.

Test	Duration [min]	Mass Released [kg]	Release Rate [g/s]	Number of Pots Burned	Configuration
1109871	25	222.1	148.1	19	side by side
1110871	36.5	229.3	104.7	20	5 stacks of 4
1110872	47.3	219.5	77.3	20	5 stacks of 4
1112871	45.7	218.5	79.7	20	5 stacks of 4
1113871	43	202.0	78.3	18	3 stacks of 4, 2 stacks of 3

Table 2. Chemical composition of HC smoke pot mixture.

By Compound

<u>Chemical Compound</u>	<u>Chemical Formula</u>	<u>Mass Fraction [%]</u>
zinc oxide	ZnO	46.6*
hexachloroethane	C ₂ Cl ₆	46.7*
grained aluminum	Al	6.7*

By Element

<u>Element</u>	<u>Fraction of Total</u>	<u>Ratio to Zinc</u>
aluminum	6.7	0.18
carbon	4.8	0.13
chlorine	41.9	1.12
oxygen	9.2	0.25
zinc	37.4	1.00

* reported by Katz (1980)

Chromel-Alumel (Type K) thermocouple positioned at the exit of the topmost pot. In addition to the obvious difficulty associated with establishing and maintaining the proper thermocouple position, the black, carbon-like material referred to earlier collected on the thermocouple forming a spherical mass approximately 2 cm in diameter. Although it is unknown to what extent this material affected the observed temperature, it is clear that only a crude determination of the exit temperature is possible given the combination of severe problems inherent in this measurement.

The mass and temperature (when measured) were sampled at 1-s intervals using a Campbell Scientific 21X Micrologger. A Zenith Z-181 portable computer was connected to the Micrologger for archiving the data to floppy disk.

2.2.2 Chemical Composition

The recipe for making the HC smoke pot calls for mixing approximately equal amounts of hexachloroethane and zinc oxide and then adding grained aluminum metal to vary the rate of burning. Specifically, design specifications call for the mass ratio of hexachloroethane to zinc oxide to be between 1.00 and 1.04. Additionally, the bulk of the mixture is maintained at 5 – 7% aluminum metal, whereas the faster-burning starter mixture contains 7 – 11% aluminum. Given the difficulty involved in obtaining a representative sample, no attempt was made to determine the composition of the pots directly. Rather, it was decided that the design specifications and the published data of Katz et al. (1980) provided better information on pot composition than was possible to obtain under field test conditions. Table 2 gives the initial composition on both a compound and an element basis. As we shall see later, we treat zinc as a conservative tracer in our dispersion experiments. Thus, it is particularly useful to scale the mass fraction of each component by the mass fraction of elemental zinc.

2.3 Meteorological Measurements

Owing to the simple terrain and the attendant horizontal uniformity of the wind field, the measurement of a single vertical profile near the center of the test site was deemed adequate for our purpose. To supplement this information and to provide additional data useful in locating the source for a particular trial, the wind speed, wind direction and temperature were measured upwind of the anticipated release point using a 2-m mast. An attempt was also made to operate a tethered instrument balloon to obtain data on the vertical structure of the boundary layer, but this approach proved

unsuccessful and was subsequently abandoned. As a result, the mixing depth was determined by alternative means as is more fully described by Liljegren et al. (1989).

The single vertical profile near the center of the sampling grid was determined using a 10-m instrument tower equipped with wind and temperature sensors at heights of 2, 4, 6, and 10 m. Wind speed was measured at all four heights on the tower using cup anemometers. Horizontal and vertical wind direction were determined at the three upper-most levels using bivanes, and horizontal wind direction alone was measured at the 2-m level using a single vane. Temperature was measured at all four levels using thermistors mounted in aspirated radiation shields. The outputs of all tower instruments were sampled at 1-s intervals using a Campbell Scientific 21X Micrologger coupled to a Zenith Z-181 portable computer for archiving the data onto floppy disks.

The 2-m mast located upwind of the source was equipped with (i) a combination four-blade propellor anemometer and polystyrene wind vane and (ii) a thermistor temperature sensor mounted in a naturally aspirated radiation shield. The output of these instruments was sampled with the same equipment used to monitor the source mass and exit temperature.

2.4 Aerosol Sampling Equipment

2.4.1 Particle Phase

The system for sampling the particle phase of the HC smoke consisted of 46 masts organized into four transects as previously described. A sampling mast consists of an 8-m long, thin-walled aluminum tube to which pipe fittings are welded at 1-m intervals. The sampling mast is supported vertically during operation thus allowing multiple heights to be sampled simultaneously. For both the fog-oil and HC smoke trials, filter cassettes were attached to each mast at the 1-m, 2-m, 4-m and 8-m levels. Aspiration was provided by a 450-W, AC-powered air pump, the total flow rate through each mast being regulated by a valved rotameter. Due to the manifold effect of the large diameter mast, the flow rate through each filter cassette is simply the total aspiration rate divided by the number of cassettes. The flow rate for a single cassette was 18.1 lpm in all cases except for those on Transect 1 during Test 1113871 for which the flow rate was 10.8 lpm. A total of 920 filter samples ($5 \text{ trials} \times 46 \text{ masts} \times 4 \text{ levels}$) were collected during the HC smoke trials.

The filter cassette used to collect the HC smoke particulate consists of a clear acrylic housing approximately 45 mm in diameter and 55 mm long with a hose nipple

centered in one end. The other end of the cassette is closed except for a small opening. Air is drawn axially through the cassette and the particulate material removed by a 37-mm filter covering the cylindrical end nearer the exit. A cellulose membrane filter with a pore size of 0.45 μm was used for HC smoke. The filter cassette is attached to the nipple of the sampling mast with a short length of silicone rubber hose.

The filter cassette used to sample the HC smoke differs from the one used to sample the fog-oil smoke in two respects. First, a cellulose membrane filter was substituted for the glass-fiber filter used to collect the fog-oil smoke. This was done because the glass-fiber filter contains trace metals which interfere with the chemical analysis procedure. Basically, an organic filter was used to collect an inorganic smoke particulate in the case of HC, and an inorganic filter was used to collect an organic smoke material in the case of fog oil. The second difference concerns the inlet geometry of the filter cassettes. The inlet side of the cassette used in the HC tests was closed except for a small central hole about 5 mm in diameter. For the fog-oil tests, the inlet was completely open the full 37-mm diameter of the filter. This difference which arose from the basic nature of the two commercially manufactured cassettes is not expected to significantly affect sampling of the smoke.

2.4.2 Vapor Phase

Previous studies have indicated the existence of several potentially harmful organic compounds in the vapor phase of HC smoke. To verify the existence of these compounds and to determine their relative mass fractions, twelve samples of the vapor phase were collected as part of the five dispersion trials. A filter cassette in series with a Tenax-filled stainless steel tube was used for this purpose. The particulate phase of the smoke is first removed by the filter and then the remaining vapor is adsorbed onto the Tenax. The filter cassette used was of the type described above, and the stainless steel tube was approximately 6 mm in diameter and 90 mm long. The resulting filter/tube sampler was aspirated at the rate of 100 ml/min by a battery-powered Gilian pump. The sampling tubes were carefully conditioned before each test and then stored inside screw-top glass tubes to avoid contamination. After exposure, the tubes were once again sealed inside the glass tubes until the chemical analysis could be carried out.

2.5 Particle Size Measurements

Particle size was measured using a Model PC-2 quartz-crystal-microbalance cascade impactor manufactured by California Measurements, Inc. The cascade impactor of the PC-2 consists of 10 stages, each of which is a vibrating quartz crystal. As particles deposit on the crystal, the frequency of vibration decreases. The frequency change of each stage is measured and the corresponding mass determined.

The cutoff size for each successive stage decreases by a factor of roughly 2. Thus, the cutoff size of the first stage is roughly 2^9 or about 500 times that of the last stage. This progression of cutoff sizes gives the instrument an enormous range. Moreover, cutoff size depends on the inverse square root of the aerosol particle density in an aerodynamic sizing instrument like a cascade impactor. For HC smoke, the particle density is not known exactly since the nature of the aerosol particle itself is disputed among various investigators. The density is effectively bounded, however, by the density of crystalline zinc chloride (2900 kg/m^3) at the high end and by the density of liquid water (1000 kg/m^3) at the low end. Lacking more precise information, we have based our determinations on an assumed density of 2000 kg/m^3 .

3. CHEMICAL ANALYSIS METHODS

The 920 filter samples collected in our five HC smoke trials were processed by Coors Analytical Laboratory of Boulder, Colorado. The mass of zinc and aluminum was determined for all of the filter samples. These data will serve as the primary basis for evaluating dispersion models. In addition, 32 of the most heavily exposed filters were selected for more detailed analysis. One phase involved an anion analysis of all 32 of the selected samples for bromide, chloride, iodide, nitrate and sulfate. A second phase involved a 40-element analysis of 10 of the samples along with an analysis of the remaining 22 samples for arsenic, cadmium, mercury and lead. The objective of the more detailed analysis was to learn as much about the chemical composition of the HC smoke as was possible given the limitations inherent in a field study.

The vapor samples taken during the HC smoke trials were analyzed for tetrachloromethane, tetrachloroethylene, hexachloroethane, and hexachlorobenzene using a thermal-desorption gas chromatography system. It was not possible within the limitations of the project to identify all the components of the vapor phase. Rather the objective was to verify the existence of these four potentially harmful vapors and to quantify their relative importance.

3.1 Analysis of Filter Samples

The analysis of the filter samples was accomplished by first digesting them in nitric acid and then analyzing the resulting liquid for specific elements. To effect the digestion, the samples were placed in clean, dry 150-ml beakers and a 100- μ l aliquot of 1000-mg/l cobalt added as an internal standard. Then, a 2.5-ml aliquot of very high purity nitric acid was added, a refluxing watch glass placed over the beaker, and the sample heated for fifteen minutes over medium heat to dissolve the filter. The sample was not allowed to evaporate to dryness. The samples were quantitatively transferred to 10-ml test tubes, rinsing with 5% very high purity nitric acid. The test tubes were capped and the contents manually mixed by shaking the tubes.

All of the analyses, except for the anion determinations, were carried out using an inductively coupled argon plasma atomic emission spectrometer technique on the Model 1100 Thermo Jarrell Ash system with normal aqueous aerosol sample introduction. In this technique, a sample of the liquid solution is sprayed into an argon plasma. The atomic emission spectra produced by the sample are then used to quantify the elements of interest. The plasma excitation source is responsible for the exceptional sensitivity of this instrument. In addition, a hydride technique was used for arsenic and selenium, and the analysis for bromide, chloride, iodide, nitrate and sulfate was carried out using ion chromatography.

All methods are those which Coors Analytical Laboratory has developed over a period of years for analyzing filter samples of airborne particulates. The methods used reflect the specific capabilities of their equipment as well as their considerable experience in this area.

3.2 Analysis of Vapor Samples

The vapor phase of the HC smoke was analyzed using a Perkin-Elmer Sigma 300 Gas Chromatograph. Reduction of data from the chromatograph was carried out using a Perkin-Elmer LCI-100 Integrator linked to a Perkin-Elmer Model 7500 Computer. The key parameters of the method are summarized in Table 3.

The injector of the chromatograph was modified to permit complete insertion of the Tenax-filled collection tubes. Once a tube is secured in the modified injector, nitrogen gas is passed through the tube at the rate of 70 ml/min. The flow leaving the injector is split into equal streams, one of which is directed through the packed column of the chromatograph. Because the injector is held at 300 °C, the collected vapor

Table 3. Key parameters of gas chromatography method used to analyze HC smoke vapor samples.

Chromatograph:	Perkin-Elmer Sigma 300 with LCI-100 Integrator and Model 7500 Computer
Detector:	Flame Ionization
Column:	12 ft., 1/4 in OD, AP-L 15%, Chrom W 80/100 mesh
Temperatures:	
Modified Injector	300 °C
Detector	350 °C
Column	
Initial	20 °C for 5 min.
Ramp	8 C°/min for 35 min.
Final	300 °C for 20 min.
Carrier gas:	Ultra-pure Nitrogen
Flow rates:	
Modified Injector	70 ml/min
Column	35 ml/min
Bypass Flowrate	35 ml/min
Analysis time:	60 min

desorbs from the Tenax and is transferred by the flowing gas to the column. To ensure that the sample will collect at the head of the column, the column temperature is held at 20 °C using liquid nitrogen for a period of 5 min. after the tube is placed in the injector. The column temperature is then raised at the rate of 8 C°/min. to a value of 300 °C, where it is held constant for a period of 20 min. The flow through the column is maintained at 35 ml/min. throughout the analysis. The various components of the vapor sample pass off the non-polar column in order of increasing molecular weight. The output of a flame ionization detector is integrated to determine the amount of each compound leaving the column.

The instrument was calibrated by analyzing pure samples of tetrachloromethane, tetrachloroethylene, hexachloroethane, and hexachlorobenzene. The solid hexachloroethane and hexachlorobenzene were dissolved in hexane at the rate of 1 mg/l and the resulting solution added to clean Tenax-filled sample tubes. Analysis of these tubes allowed the elution time and detector sensitivity to be determined for these two compounds. The volatile tetrachloromethane and tetrachloroethylene liquids were aspirated onto clean Tenax-filled sample tubes which were analyzed to determine the elution times. Calibration of the detector for these vapor samples was accomplished by first determining the sensitivity for n-dodecane and hexane, then calculating the effective sensitivity for tetrachloromethane and tetrachloroethylene based on proportionality to carbon concentration.

4. RESULTS

4.1 Source and Meteorological Measurements

A compilation of the relevant source and meteorological variables for the HC smoke trials is given in Table 4. These data represent averages over the period of each test. Source locations are given in the coordinate system defined by the sampling grid shown in Fig. 2. The mean wind speed and horizontal direction are denoted by $\bar{u}$ and θ , respectively. The vertical wind direction is denoted by ϕ and is assumed to be 0° in the mean. The symbol σ is used to denote a standard deviation with the subscript indicating the variable of interest. For example, the combination σ_θ denotes the standard deviation in the horizontal wind direction θ . The wind-vector components u , v , and w refer to the downwind, crosswind and vertical directions, respectively. The downwind and crosswind components are defined relative to the mean wind direction

Table 4. Source and meteorological data for the HC smoke dispersion trials.

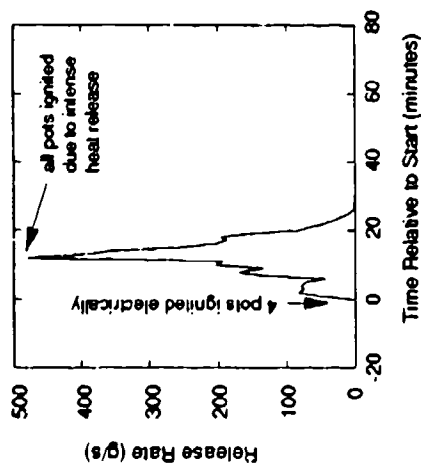
General Information					
Test Designation	1109871	1110871	1110872	1112871	1113871
Date	9 Nov 87	10 Nov 87	10 Nov 87	12 Nov 87	13 Nov 87
Begin Time (CST)	15:45:00	11:27:30	16:37:41	13:31:20	10:21:00
End End (CST)	16:10:00	12:04:00	17:25:00	14:17:00	11:04:00
Duration (MM:SS)	25:00	36:30	47:19	45:40	43:00
Source Location (See Figure 2)					
x position (m)	270.3	270.3	270.3	-21.1	-21.1
y position (m)	470.8	470.8	470.8	21.1	21.1
Summary of Near-source Measurements (2-m height)					
Mean wind speed, $\bar{u}$ (m/s)	2.3	3.6	2.5	1.9	1.9
Mean wind direction, θ ($^{\circ}$ E of N)	12	26	13	220	221
Std. dev. in hor. wind dir., σ_{θ} ($^{\circ}$)	18.7	19.7	19.9	28.6	31.2
Temperature, T ($^{\circ}$ C)	5.9	3.2	3.0	13.8	12.9
Relative humidity, RH (%)	69	61	49	35	45
Summary of Instrument Tower Measurements (10-m height)					
Wind speed, $\bar{u}$ (m/s)	4.4	7.1	5.2	4.9	4.3
Wind direction, θ ($^{\circ}$ E of N)	25	34	24	226	241
Standard deviations:					
σ_{θ} ($^{\circ}$)	11.0	13.2	14.4	15.3	15.5
σ_{ϕ} ($^{\circ}$)	8.0	9.3	8.3	9.8	9.9
σ_u (m/s)	1.03	1.74	1.28	1.32	1.08
σ_v (m/s)	0.80	1.63	1.22	1.34	1.15
σ_w (m/s)	0.75	1.41	0.93	0.94	0.83
ΔT (10 m - 2 m) ($^{\circ}$ C)	-0.68	-0.95	-0.70	-0.76	-0.74
Cloud cover	heavy overcast	medium overcast	mostly cloudy	clear	clear
Summary of Scaling Parameters					
Wind speed exponent, n	0.130	0.132	0.132	0.121	0.137
Monin-Obukhov Length, L (m)	-46	-110	-68	-63	-53
Friction velocity, u_* (m/s)	0.51	0.72	0.57	0.54	0.49
Roughness height, z_0 (m)	0.20	0.20	0.20	0.20	0.20
Inversion height, z_i (m)	649	448	434	816	500
Convection velocity, w_* (m/s)	1.68	1.57	1.42	1.73	1.41

and thus the average value of u is simply the mean wind speed $\overline{u}$, and the average values of v and w are both zero.

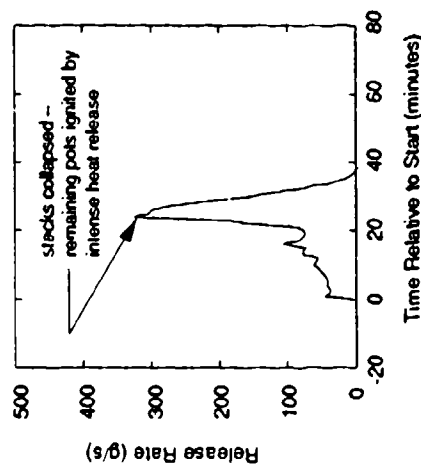
The values of several meteorological scaling variables are also summarized in Table 4. The wind exponent n is determined by fitting the measured wind speed values to the power-law form $u = a z^n$, where z is height above the ground and a and n are fitting parameters. The friction velocity u_* and the Monin-Obukhov length L are the relevant velocity and length scales in the surface layer where mechanical turbulence dominates transport. The Monin-Obukhov length L indicates the approximate height above ground to which the surface layer extends. The friction velocity u_* is determined by the shear stress at the surface and, thus, characterizes surface induced shear effects. The roughness height z_0 characterizes the roughness elements on the ground which create the mechanical turbulence in the surface layer. The convective mixed layer lies above the surface layer and extends to a height of z_i . The convective motions in the mixed layer scale with the convective velocity w_* .

The time-dependent mass rate of release is presented in Fig. 3 for four of the five tests. The results for the final test (Test 1113871) were lost due to an equipment failure, although the initial and final masses were manually recorded and thus the value given for total mass released is accurate. Recall that a single layer of 19 pots was used in Test 1109871. Figure 3 shows that about midway through the first burn, the second row of pots was ignited by the intense heat and the remaining pots were all ignited shortly thereafter. This leads to the very high release rate and short duration of the test. Test 1110871 was conducted with the pots stacked, but the stacks collapsed after about 20 minutes of the test and again a high release rate and short burn time were the result. More controlled ignition was achieved in the final three tests; results for two of these tests (Tests 1110872 and 1112871) are shown in Fig. 3. It is observed that the release rate increases significantly as each successively lower pot is ignited. The temperature measurements shown for Test 1112871 further illustrate the uneven nature of the burning, although the magnitude of the observed temperature is strongly influenced by thermocouple placement.

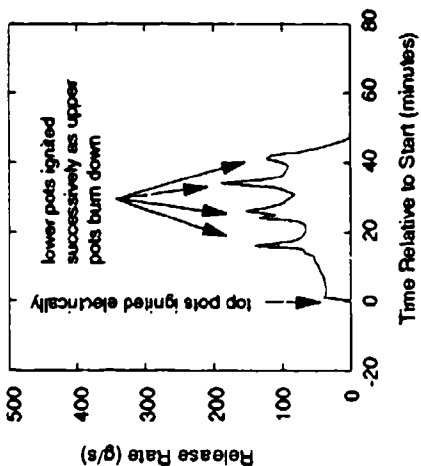
The results of the two single-pot diagnostic burns are shown in Fig. 4. One test was conducted with the pot burning upright, the second test with the pot burning laying on its side. The motivation for these tests came from reports that there is a significant difference in the burn characteristics in these two orientations, both of which are used by smoke units in the Army. The results shown in Fig. 4 indicate a substantial difference in the average exit temperatures (900 °C in the upright position versus 600 °C laying on its side), although the problems associated with duplicating the placement of



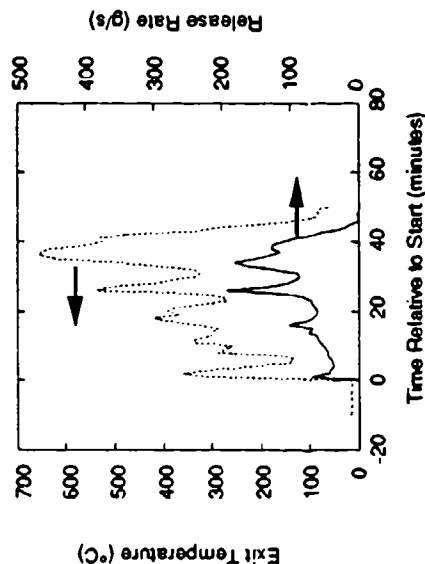
(a) Test 1109871 - 19 pots burned side by side
Duration: 25 min., Total release: 222.1 kg.
Average rate: 148.1 g/s



(b) Test 1110871 - 20 pots in 5 stacks of 4
Duration: 36.5 min., Total release: 229.3 kg.
Average rate: 104.7 g/s

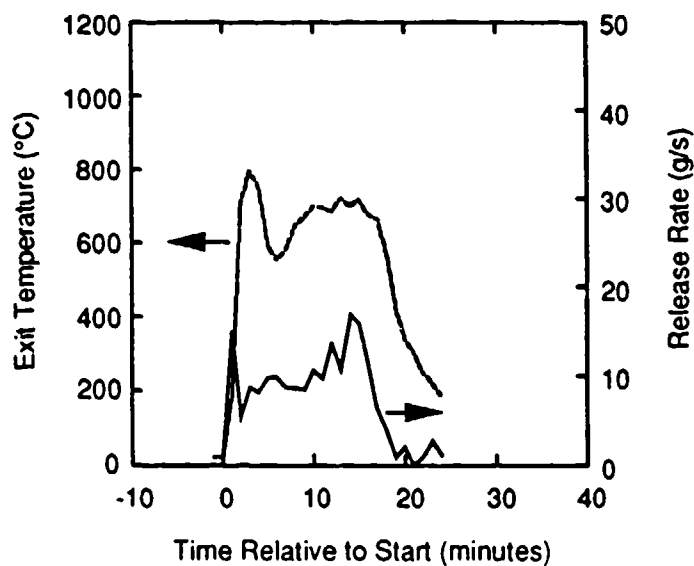


(c) Test 1110872 - 20 pots in 5 stacks of 4
Duration: 47.3 min., Total release: 219.5 kg.
Average rate: 77.3 g/s

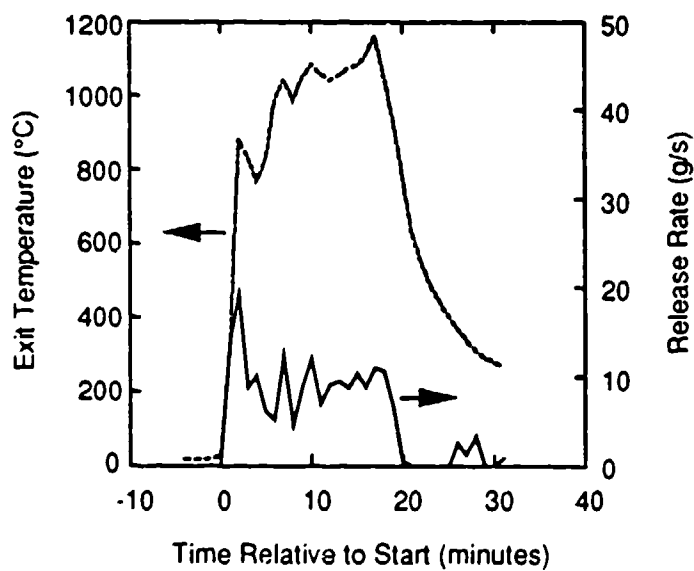


(d) Test 1112871 - 20 pots in 5 stacks of 4
Duration: 45.7 min., Total release: 218.5 kg.
Average rate: 79.7 g/s

Figure 3. One-minute averaged source data for four HC smoke trials: (a) Test 1109871, (b) Test 1110871, (c) Test 1110872 and (d) Test 1112871.



(i) Pot Lying on Side



(ii) Pot in Normal Upright Position

Figure 4. Release rates and exit temperatures for two different pot orientations: (i) pot lying on its side and (ii) pot in the normal upright position.

the thermocouple do cloud the issue somewhat. Moreover, neither the total mass released nor the duration of the burn differed significantly. If the temperature is, in fact, significantly different, then the equilibrium composition of the combustion products may be different as well due to changes in the Gibbs energy function with temperature. In a similar vein, we noticed during the full-scale releases that the downwind pots appeared to burn hotter (as evidenced by the color of the hot metal canisters) and more rapidly (as evidenced by the more rapid burn down) than the upwind pots even though the stacks were fairly close together. We attribute this behavior to the cooling effect of the wind. Analysis of such issues is well beyond the scope of the current project, although the fact that the smoke characteristics may differ depending on factors such as ambient temperature, humidity, wind speed, and even pot orientation should provide a degree of caution in generalizing the results to all possible scenarios.

More complete information concerning the source and meteorological data recorded during the Atterbury-87 Field Studies is presented in the companion report by Liljegren et al. (1989).

4.2 Particle Size

Figures 5 through 9 show the particle size distributions measured for each of the five HC smoke trials. The data are plotted on log-probability axes for which a log-normal distribution is a straight line. All of the tests show a greater fraction of smaller particles than a true log-normal distribution gives. Moreover, the mass of particles collected in this smaller size range is well above background. Thus, we may conclude that the particle size distribution is most likely bimodal and that there may, in fact, be two different types of particles present in the smoke.

The sizes shown in Figs. 5 through 9 are based on a nominal particle density of 2000 kg/m^3 . If two different types of particles are indeed present, it is likely that the larger particles are zinc chloride solution drops. In this case, particle density will be closer to that of liquid water and the cut sizes for each stage must be *increased* by a factor of about 1.2 to 1.4. In contrast, the smaller particles are most probably those which did not grow into solution drops for physical and/or chemical reasons. Thus, these particles most likely have a density greater than 2000 kg/m^3 and thus the sizes shown in Figs. 5 through 9 must be reduced accordingly. The net effect is to further separate the the larger and smaller particle size ranges over that already indicated in

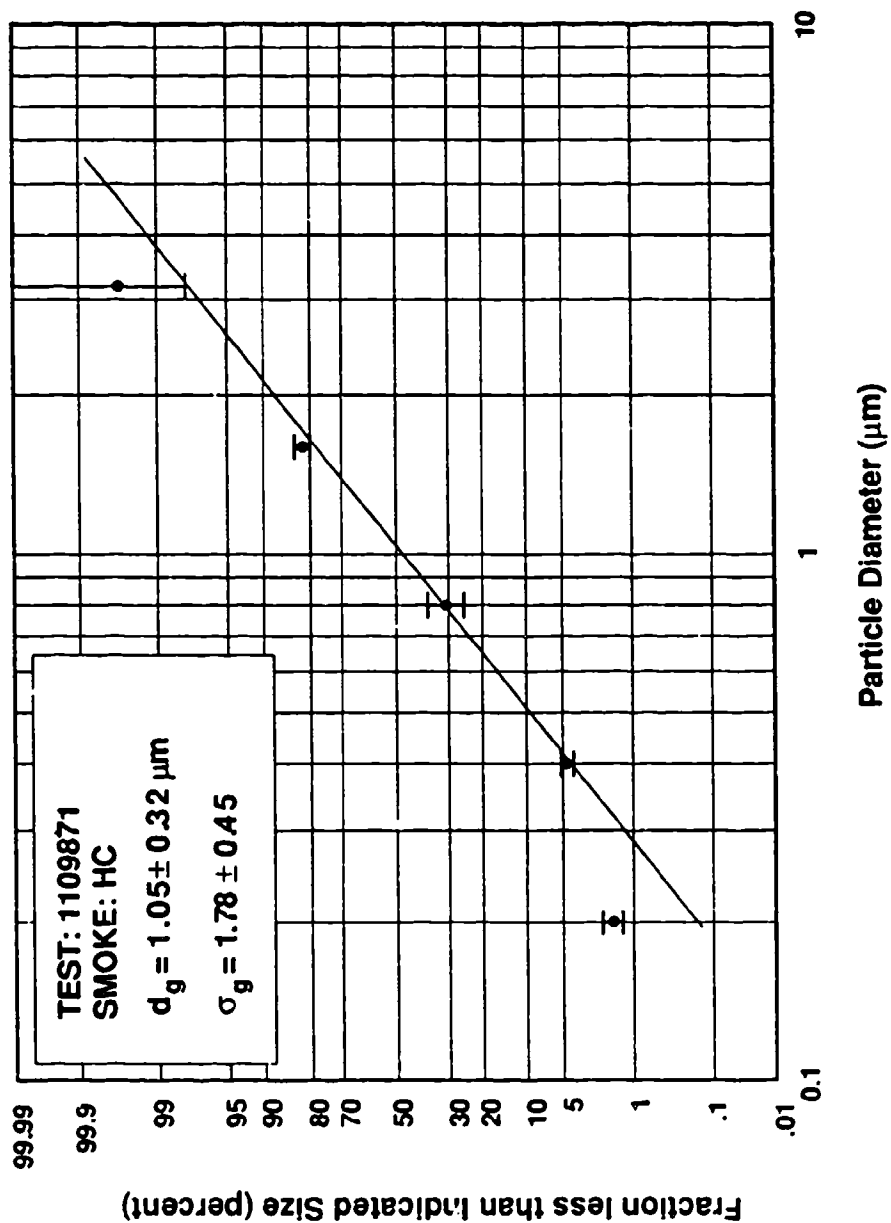


Figure 5. Particle size distribution of HC smoke measured during Test 1109871.

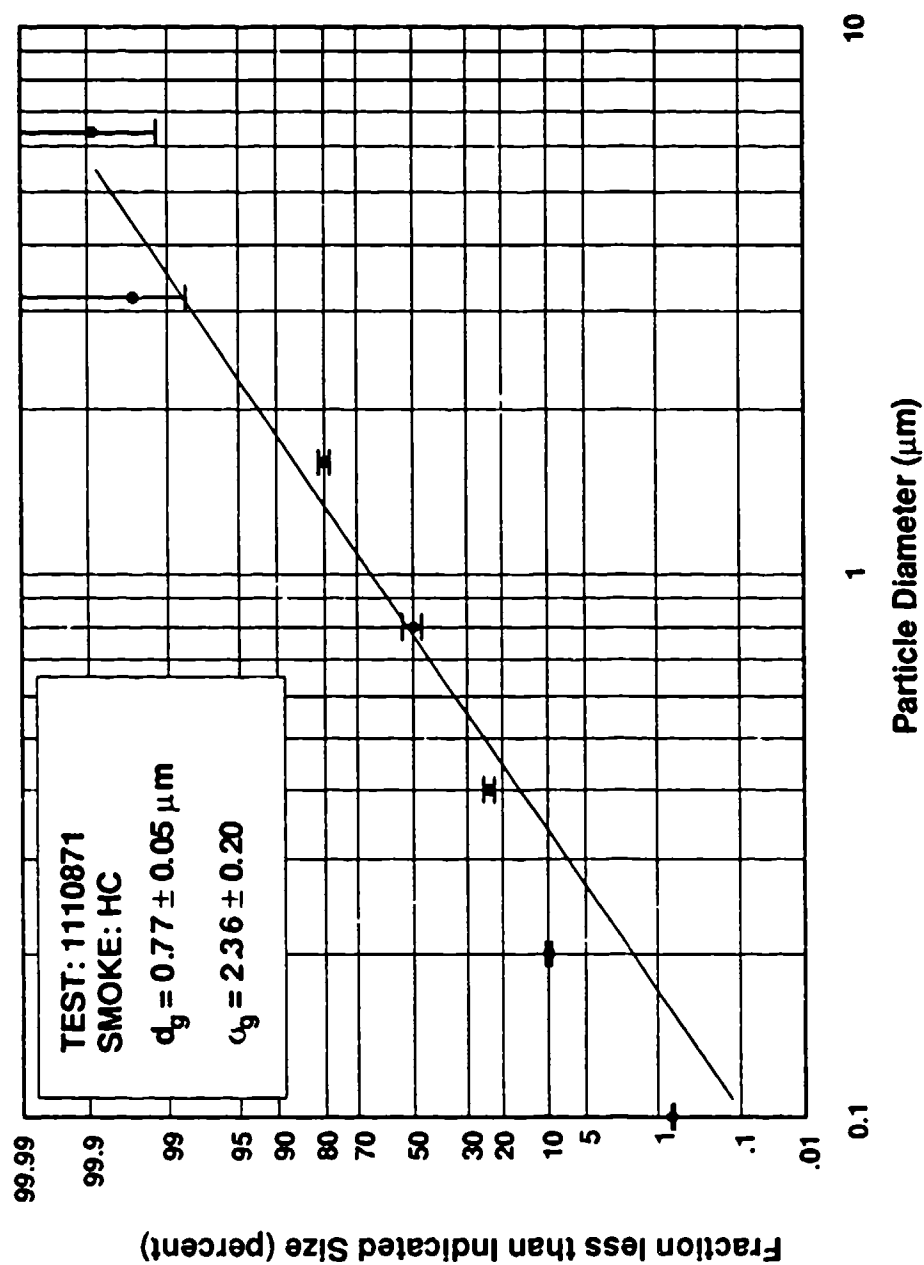


Figure 6. Particle size distribution of HC smoke measured during Test 1110871.

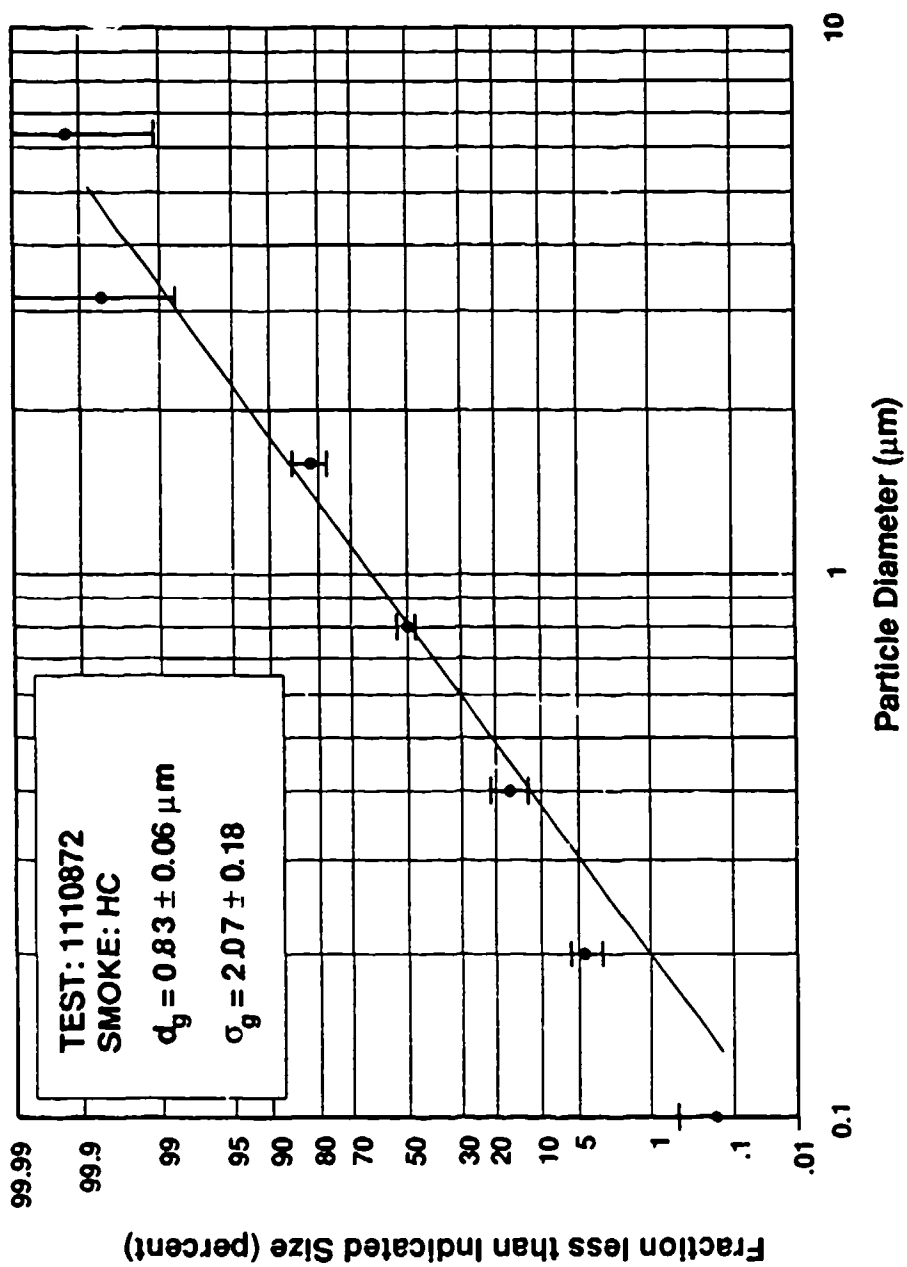


Figure 7. Particle size distribution of HC smoke measured during Test 1110872.

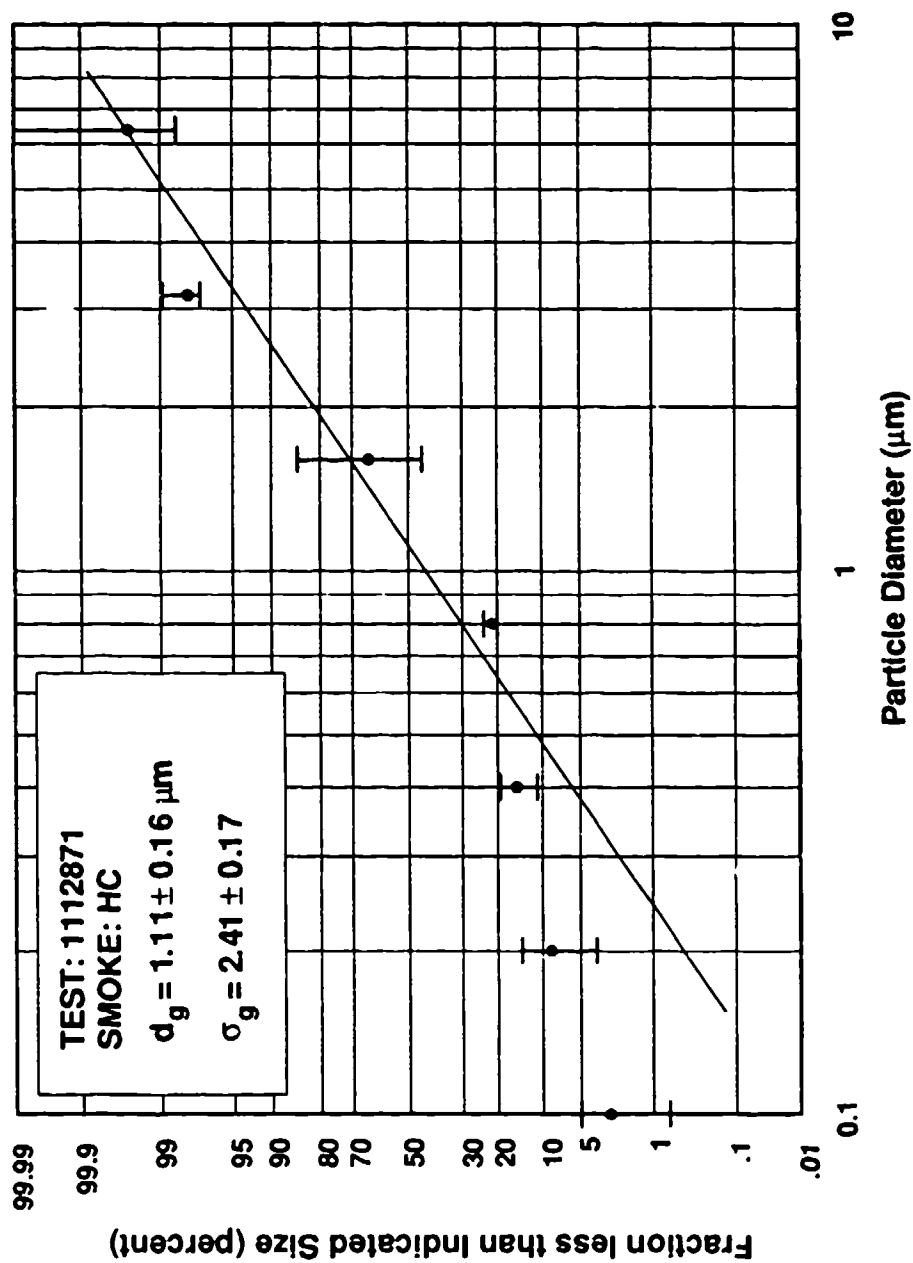


Figure 8. Particle size distribution of HC smoke measured during Test 1112871.

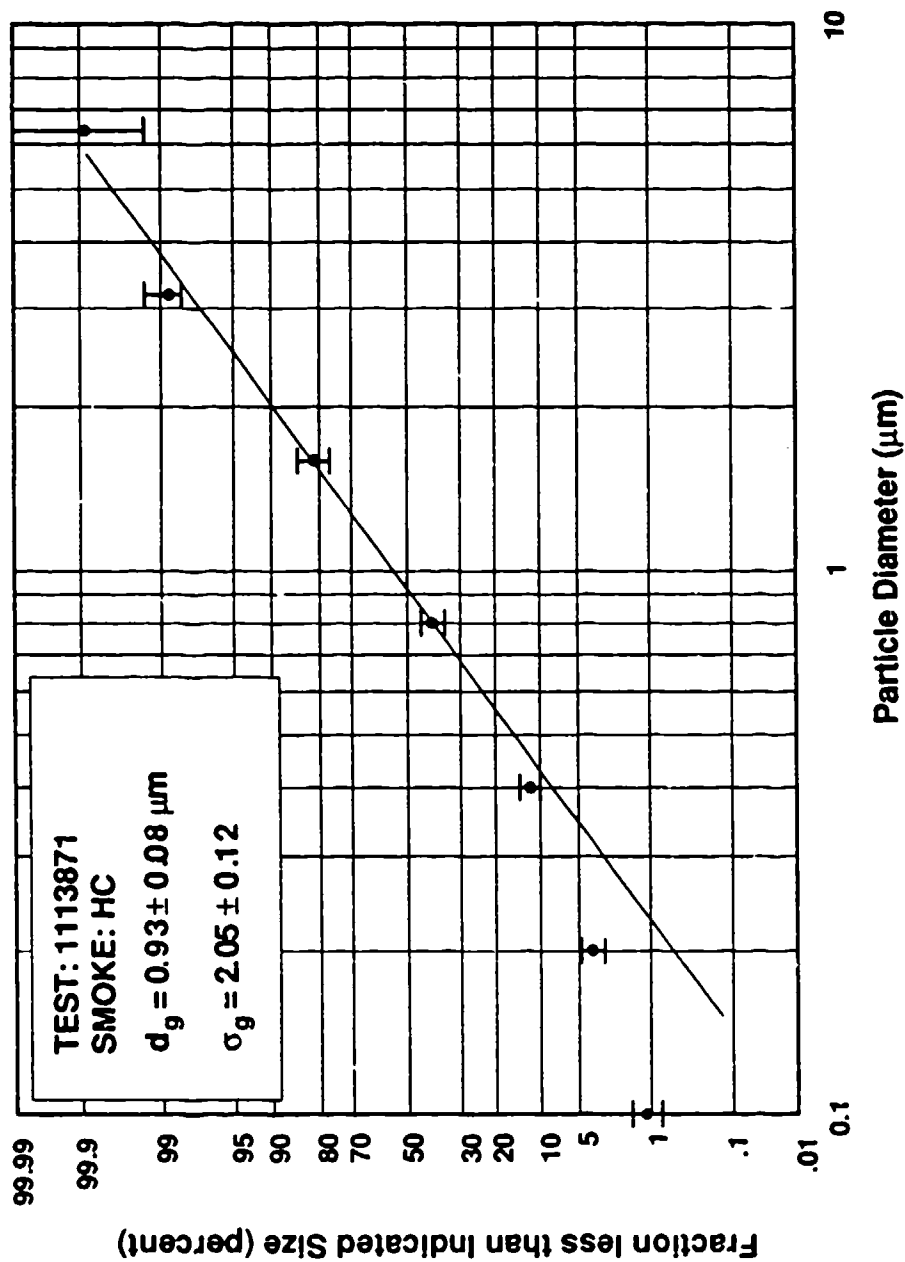


Figure 9. Particle size distribution of HC smoke measured during Test 1113871.

Figs. 5 through 9. We shall return to the matter of the bimodal particle size distribution in Section 4.3.1.

Again, only the salient features of the particle size measurements are presented here; additional detail is given by Liljegren et al. (1989).

4.3 Chemical Composition of HC Smoke

A major part of the effort devoted to HC smoke was aimed at determining the chemical composition of the HC particulate and vapor phases. In fact, the inductively coupled argon plasma atomic emission spectrometer technique was selected not only because of the accuracy with which zinc and aluminum mass determinations could be made, but also because it allowed a wide ranging analysis of the elemental composition of the filter samples. The study of the vapor phase was more limited in scope and directed primarily at four specific hydrocarbon compounds.

4.3.1 Analysis of Filter Samples

As previously described, 10 of the most heavily exposed filter samples were selected for a complete elemental analysis using an atomic emission spectrometer technique which can quantify 40 separate elements. In addition, these samples were analyzed by ion-chromatography for bromide, chloride, iodide, nitrate and sulfate. Combining these results, an analysis for a total of 45 elements is obtained. Key elements omitted from the analysis are carbon, hydrogen and oxygen, all of which are present in the HC smoke pot mixture. Detailed information concerning these elemental and anion analyses is given in Appendix C.

The results of the elemental analysis are summarized in Table 5. Here, the elements are listed in decreasing order of their average mass on the 10 filter samples. We see that zinc and chlorine are the major contributors but that many other elements are present in significant amounts as well. In order to better identify those which are present in the HC smoke particulate, we have calculated the correlation coefficient of each of the elements with zinc. From this statistic, five significant elements are identified: zinc, chlorine, iron, aluminum and lead.

The analysis of an additional 22 samples for 11 elements (zinc, aluminum, chloride, sulfate, nitrate, iodide, bromide, lead, arsenic, mercury, and cadmium) confirms the results described above. Only zinc, aluminum and chloride are identified as significant contributors. The remaining elements either are present in negligible amounts

Table 5. Elemental composition of filter samples.

Element	Average Mass [µg]	Average Mass Ratio Relative to Zinc	Standard Deviation of Mass Ratio to Zinc	Correlation Coefficient with Zinc
Zn	292.65	1.0000	0.0000	1.00
Chloride	256.40	0.8632	0.1390	0.91
Fe	66.22	0.2207	0.0721	0.73
Na	42.78	0.1553	0.0578	0.21
Al	22.55	0.0766	0.0155	0.77
Sulfate	9.00	0.0300	0.0219	0.36
Ca	8.31	0.0325	0.0273	-0.38
Pb	7.58	0.0253	0.0083	0.71
Si	3.87	0.0132	0.0081	0.36
Nitrate	3.00	0.0104	0.0045	0.34
Mg	1.27	0.0046	0.0016	-0.03
Sn	1.08	0.0042	0.0054	-0.12
Bromide	1.00	0.0048	0.0088	-0.59
Zr	0.65	0.0024	0.0009	-0.10
Ba	0.63	0.0024	0.0017	-0.15
B	0.61	0.0024	0.0033	-0.15
Cr	0.51	0.0023	0.0034	-0.65
Cu	0.33	0.0013	0.0011	-0.30
Ti	0.32	0.0015	0.0029	-0.67
P	0.30	0.0020	0.0062	-0.69
Cd	0.29	0.0010	0.0009	0.07
Ag	0.18	0.0008	0.0014	-0.42
Sb	0.15	0.0005	0.0004	0.39
V	0.14	0.0005	0.0010	0.10
Mu	0.13	0.0006	0.0010	-0.43
Ni	0.12	0.0004	0.0008	0.13
Be	0.08	0.0003	0.0002	0.25
As	0.05	0.0002	0.0001	0.30
Mn	0.04	0.0001	0.0002	0.18
Co	0.03	0.0002	0.0006	-0.69
Sr	0.02	0.0001	0.0001	0.32
Se	0.01	0.0000	0.0001	-0.04
Iodide	0.00	0.0000	0.0000	0.00
Hg	0.00	0.0000	0.0000	0.00
Au	0.00	0.0000	0.0000	0.00
Ce	0.00	0.0000	0.0000	0.00
K	0.00	0.0000	0.0000	0.00
La	0.00	0.0000	0.0000	0.00
Li	0.00	0.0000	0.0000	0.00
Nd	0.00	0.0000	0.0000	0.00
Pd	0.00	0.0000	0.0000	0.00
Pr	0.00	0.0000	0.0000	0.00
Pt	0.00	0.0000	0.0000	0.00
Th	0.00	0.0000	0.0000	0.00
Y	0.00	0.0000	0.0000	0.00

(iodide and mercury) or else show little correlation with zinc (nitrate, sulfate, bromide, arsenic and cadmium), and thus are most likely from other sources.

Table 6 compares the composition of the HC smoke particulate as determined from the analysis of the filter samples with the composition of the original mixture, all values given relative to zinc. The uncertainties shown for the smoke particulate reflect the 95% confidence level. Note that values are given based on both the 45-element analysis of 10 samples and the 11-element analysis of 22 samples. These two determinations of particulate phase composition agree within the uncertainty of the data.

Table 6 indicates that only about 77% of the chlorine and only about 43% of the aluminum is accounted for, based on the analysis of the filter samples. In contrast, a significant amount of iron was detected even though iron is not thought to be an important constituent of the original mixture. It seems likely that the iron comes from the sheet metal containers which are partially vaporized as the pot burns. The filter analysis suggests, however, that about 1 kg of iron is released for each pot. This value seems quite high given that the canister is only partially burned away. The lead which is observed is most likely attributable to an impurity in the zinc processing.

Table 6. Composition of HC smoke particulate compared with that of the original mixture. All values given are relative to zinc.

Element	HC Smoke Pot Mixture	HC Smoke Particulate	
		10 samples	22 samples
chlorine	1.12	0.86 ± 0.10	0.88 ± 0.09
oxygen	0.25	—	—
aluminum	0.18	0.077 ± 0.01	0.080 ± 0.008
carbon	0.13	—	—
iron	—	0.22 ± 0.05	—
lead	—	0.025 ± 0.006	0.026 ± 0.004

All 920 samples were analyzed for zinc and aluminum; a complete listing of the values determined by the chemical analysis procedure is given in Appendix B. A careful examination of these data reveals that the background levels are roughly

0.5 μg for zinc and 0.7 μg for aluminum. Further analysis of the data reveals that the correlation between aluminum and zinc drops off significantly for samples which are below about three times background (1.5 μg for zinc and 2.1 μg for aluminum). These limits were therefore selected as the thresholds for a valid determination. Of the 920 samples collected, 428 have both zinc and aluminum values above the corresponding threshold. The most heavily exposed filter samples have zinc values which are roughly 300 times the threshold or about 900 times background. For aluminum, the highest values are roughly 25 times threshold or about 75 times background.

One might expect that these data would merely confirm the composition of the smoke particulate determined from the more detailed analysis presented above. Unfortunately, this was not the case. Rather, the aluminum-zinc ratio showed a wide scatter with a much lower mean than the value of roughly 0.08 stated above. The data seemed to show an underlying systematic structure, although this structure proved very difficult to uncover. It seems that the data can be divided into two distinct groups roughly based on the mass of zinc (and thus the mass of particulate smoke) collected on the filter. This dichotomous behavior is illustrated rather dramatically in Fig. 10. Here, the aluminum-zinc ratio is plotted versus mass of zinc collected for all 38 of the valid measurements taken on Transect 1 during Test 1113871. It may be observed that the aluminum-zinc ratio drops sharply from about 0.08 for zinc values above 220 μg to about 0.02 for zinc values below 200 μg . The other data show a similar behavior but the zinc level at which the transition occurs varies from case to case. Unfortunately, the factors determining the transition point could not be effectively isolated.

Owing to the variability of the transition point, it was decided to divide the data into three groups: Group 1 – samples with less than 200 μg of zinc on the filter, Group 2 – samples with between 200 and 300 μg of zinc on the filter and Group 3 – samples with more than 300 μg of zinc on the filter. Figure 11 compares the distributions of Groups 1 and 3. The distribution of Group 2 which exhibits characteristics of both of these extremes is not shown. The Group 1 distribution is very nearly log-normal with a geometric mean of 0.019 and a geometric standard deviation of 2.52. Figure 11 shows that there is a 95% probability that the aluminum-zinc ratio for a sample in Group 1 will lie between 0.0025 and 0.08, a factor of 32 in range. The log-normal distribution with a very large range suggests that the amount of aluminum collected on the filter is determined by some unknown set of random processes. In contrast, the distribution of values in Group 3 is more narrow and is equally well described by both a linear-normal and log-normal distribution. This behavior suggests that the Group 3

Variation of Al/Zn Ratio with Mass of Zinc Collected on Filter

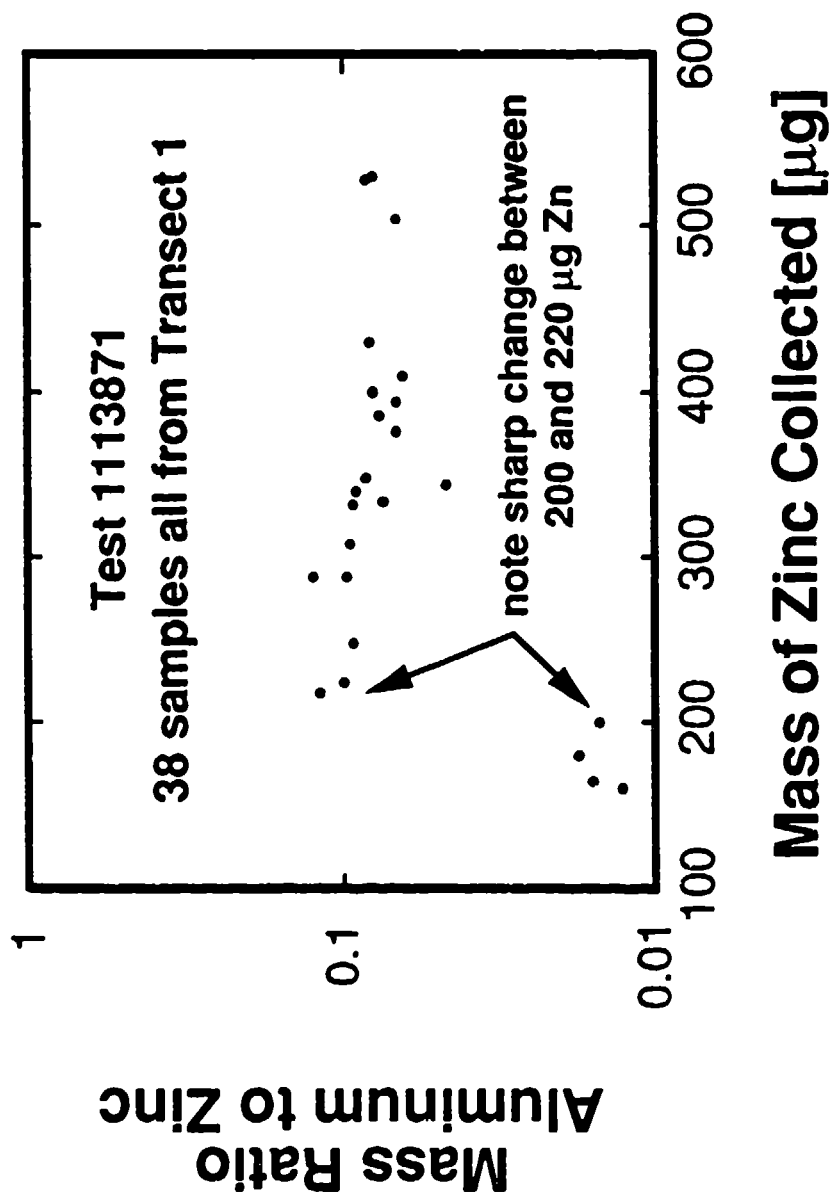


Figure 10. Variation in the aluminum/zinc mass ratio with mass of zinc collected on filter.

Cumulative Distribution of the Ratio of Aluminum to Zinc

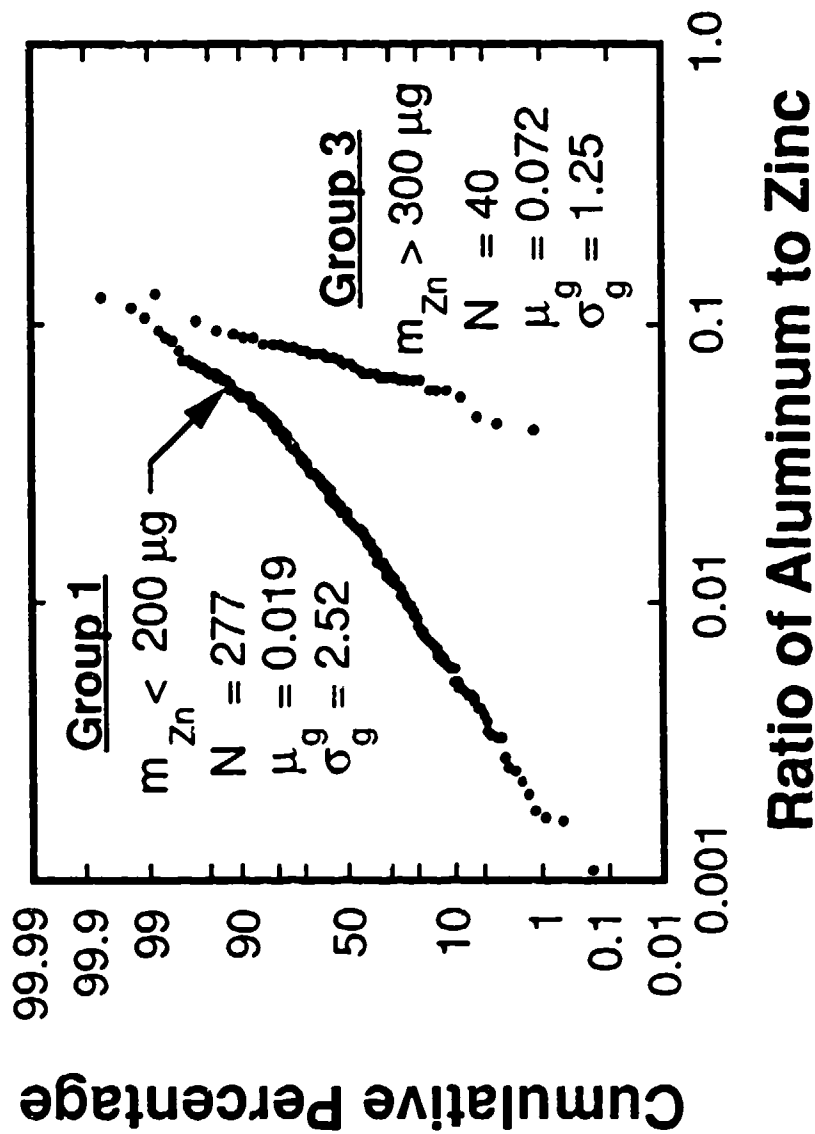


Figure 11. Cumulative distribution of aluminum/zinc mass ratio for two groups of samples:
 Group 1 – samples with less than 200 μg of zinc collected on the filter and
 Group 3 – samples with more than 300 μg of zinc collected on the filter.

distribution is the result of random measurement errors in the zinc and aluminum levels.

We can only speculate as to the cause of this strange behavior, but one possible explanation centers on the effectiveness of the filters for collecting very small particles. Recall that the particle size measurements revealed that the distribution is bimodal and that roughly 5 – 15% of the mass is contained in the smaller range. Suppose for the sake of argument that these small particles are in fact crystalline aluminum oxide and that the larger particles are zinc chloride and liquid water absorbed from the air. Accounting for the greater density of aluminum oxide ($3500 - 4000 \text{ kg/m}^3$ depending on crystal structure), we conclude that these smaller particles are log-normally distributed with a geometric mean diameter of about $0.1 \text{ }\mu\text{m}$. Such particles could ostensibly pass through a membrane filter with a pore size of $0.45 \text{ }\mu\text{m}$ such as was used to collect the particulate phase of the HC smoke. As the larger particles are deposited on the filter, the collection efficiency for the smaller particles may be expected to increase. Within the context of this scenario, the wide ranging log-normal distribution of the aluminum-zinc ratio at low filter loading can be explained in terms of the random factors influencing the collection of small particles, whereas the more narrow distribution characteristic of the more heavily exposed filters can be viewed as the result of random factors inherent in the sampling and analysis procedures.

4.3.2 Analysis of Vapor Samples

The composition of the vapor phase was studied by Katz et al. (1980). These investigators give the composition shown in Table 7. Here, the existence of many possible constituents as well as the wide variability in composition is readily observed.

Owing to the limitations inherent in the current project, our attention was focused on four of the suspected vapor-phase constituents identified as being of particular concern to USABRDL: tetrachloromethane, tetrachloroethylene, hexachloroethane, and hexachlorobenzene. The vapor phase collected in the field using Texax-filled sample tubes was desorbed and analyzed by gas chromatography in the laboratory. The methods used to quantify these compounds are described in Section 3.2. A sample chromatogram is shown in Fig. 12. This chromatogram is for the sample taken at a height of 1 m near Mast 7 of Transect 4 during Test 1110872. Detailed information for all 12 of the vapor phase analyses is provided in Appendix D.

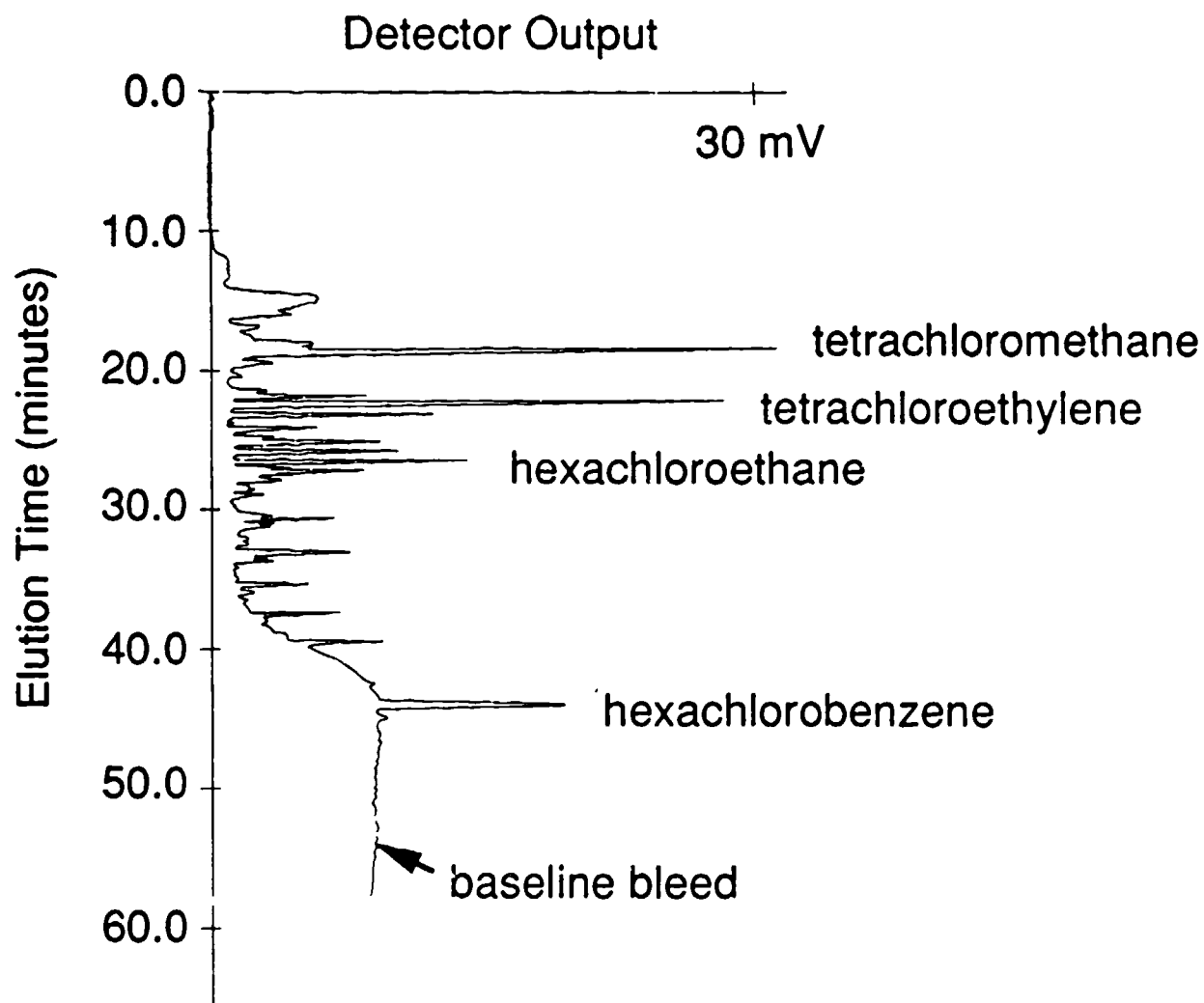


Figure 12. Sample chromatogram for HC vapor phase. This sample was collected at a height of 1 m near Mast 7 of Transect 4 during Test 1110872.

Table 7. Gaseous combustion products of HC smoke according to Katz et al. (1980).

<u>Compound</u>	<u>Formula</u>	<u>Mass Percent of Reagent</u>
tetrachloroethylene	C_2Cl_4	3.0 - 17.0 %
tetrachloromethane	CCl_4	1.0 - 3.0 %
hexachloroethane	C_2Cl_6	0.3 - 5.0 %
carbonyl chloride	$COCl_2$	0.1 - 1.0 %
hexachlorobenzene	C_6Cl_6	0.4 - 0.9 %
carbon monoxide	CO	0.9 - 3.7 %
hydrogen chloride	HCl	0.03 - 3.4 %
chlorine	Cl_2	0.3 - 1.9 %

The mass of each of these four organic compounds was scaled by the mass of zinc collected by the corresponding filter sampler in order to normalize the data. Figure 13 and Table 8 present the final results of this analysis. Figure 13 shows the cumulative distribution for each of the four vapor constituents. From this plot, we conclude that the mass fractions are log-normally distributed with a geometric standard deviation of between 7 and 11.5, very large values indeed. Such a large geometric standard deviation is consistent with the results reported Katz et al. (1980). Hexachlorobenzene is the largest contributor among the four accounting for 47.6% of the total. Tetrachloromethane is the second largest contributor at about 22% of the total. Hexachloroethane and tetrachloroethylene are about equal in their contributions being 15.8% and 14.3%, respectively. The four compounds total about 0.063 compared with the mass of zinc.

We can combine the results of the particulate and vapor phase analyses to specify the overall composition of the HC smoke. Unfortunately, the information available is insufficient to develop a complete picture. However, a reasonable approximation can be obtained by adding the following assumptions to the specific results of the particulate and vapor phase analyses.

1. Chlorine is conserved; the amount not accounted for in the particulate analysis exists in the form of chlorinated vapors.

Cumulative Distribution of Four Organic Vapors

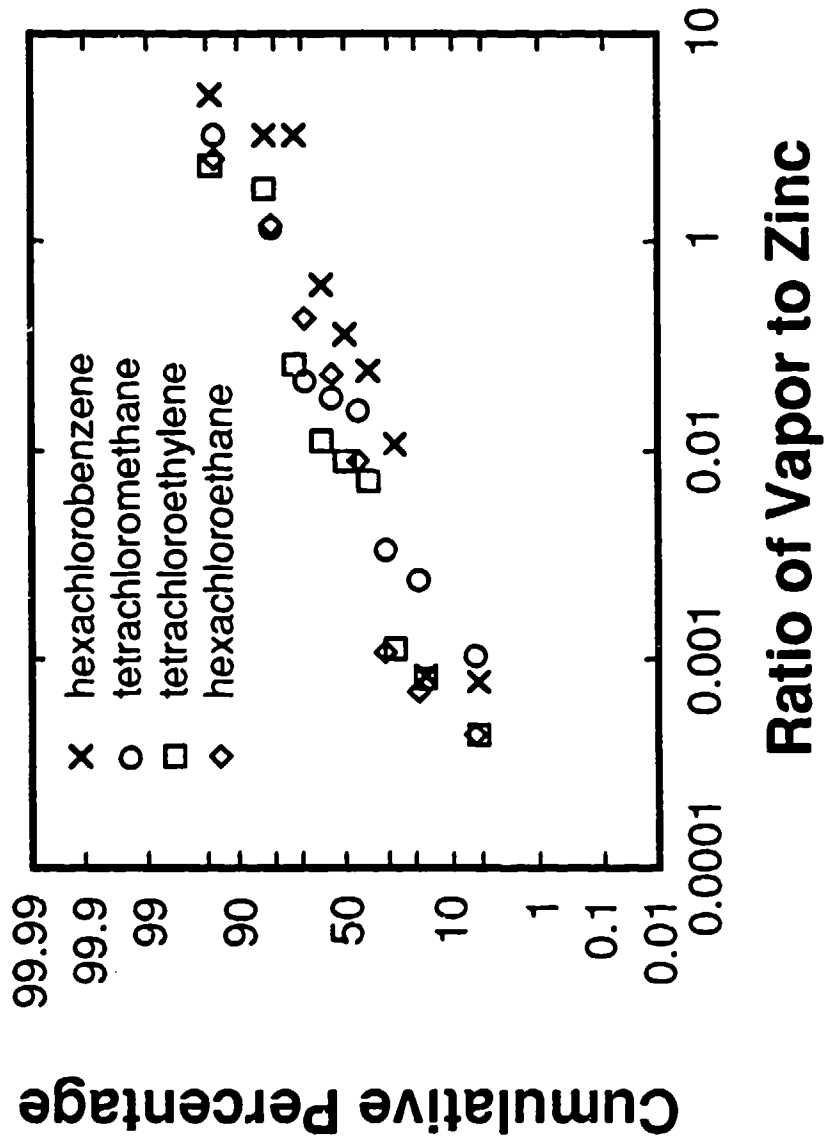


Figure 13. Cumulative distribution of four organic compounds present in the HC vapor phase.

Table 8. Composition of HC-smoke vapor phase. Values shown are relative to zinc.

Compound	Mass Ratio to Elemental Zinc			
	geometric mean	95 % confidence interval		geometric std. dev.
		lower limit	upper limit	
tetrachloromethane	0.014	0.003	0.064	7.0
tetrachloroethylene	0.009	0.002	0.049	9.4
hexachloroethane	0.010	0.002	0.064	11.4
hexachlorobenzene	0.030	0.005	0.195	11.5
four compounds combined	0.063	0.011	0.364	9.8

- Owing to its larger molecular weight relative to carbon, hydrogen and oxygen and to its usually larger atom count within the molecules of the vapor phase constituents, we assume that chlorine accounts for 90% of the vapor phase by mass.
- The metals in the particulate phase (iron, aluminum, lead and unchlorinated zinc) are all present in oxide form.

Table 9 shows the composition of the smoke using the results of the chemical analysis coupled with the above set of assumptions. This is the composition which may be expected just after the combustion products have condensed and the particulate phase is formed. As noted earlier, many believe that the zinc chloride particles then collect water from the atmosphere to form solution droplets which ultimately comprise the smoke. We cannot confirm or deny this hypothesis. Because the amount of liquid water present in the smoke is unknown, it is not taken into consideration in Table 9. The four organic vapors specifically identified in our study comprise about a third of the total vapor phase. The remainder corresponds to the peaks seen in the chromatogram but not specifically identified as well as other gases which are not collected by the Tenax absorbent.

A significant point which must be stressed in presenting the approximate composition of Table 9 is the great variability which is possible in a single sample of the smoke. Our measurements reveal that any single sample may be less than 1% vapor or more than 30% vapor with a 10% probability. Similar variation is possible in the composition of the particulate phase. Thus, individual exposures may differ greatly from the composition shown in Table 9 even for the same source and meteorological conditions.

Table 9. Approximate composition of HC smoke.

<u>Constituent</u>	<u>Estimated Mass Fraction (%)</u>
zinc chloride	62.5
zinc oxide	9.6
iron oxide	10.7
aluminum oxide	5.4
lead oxide	<u>1.0</u>
Total particulate phase	89.2
chlorinated vapors	<u>10.8</u>
Total particulate and vapor phases	100.0

4.4 Concentration Measurements

The discussion to this point has centered on characterizing the HC smoke in physical and chemical terms. An equally important objective of our study is the acquisition of data for evaluating and improving atmospheric dispersion models. These data are presented in terms of the mean concentration calculated by taking the ratio of the total mass collected on a filter sample to the product of the aspiration rate and the duration of the release. Since the exact composition of the smoke is only approximately known, we chose instead to base our analysis on elemental zinc which acts as a conservative tracer in the smoke. All of the zinc ostensibly exists in the particulate phase and thus is collected by the filter samplers.

Unfortunately, an apparent problem with the sampling method was discovered after the data were taken. It appears that filter loading significantly affects collection efficiency. This problem is most likely related to the nature of the membrane filter used to collect the HC smoke and is probably made more severe by the fact that liquid water surrounds the much smaller zinc chloride particle. As a result of this loading effect, the most heavily exposed filter samples showed lower levels of zinc than were actually present.

To study the effect of filter loading, we begin with a simple equation relating the collection rate dm/dt to the atmospheric concentration C and the nominal flow rate $\dot{V}_0$. Written in terms of zinc, we have

$$\frac{dm_{zn}}{dt} = \epsilon(m_{zn}) C_{zn} \dot{V}_o, \quad (4.1)$$

where ϵ is the collection efficiency which is assumed to depend on the mass collected. We can estimate ϵ by comparing the results obtained from the filters aspirated at the rate of 0.1 lpm by a battery-powered Gilian pump with those obtained from the nearby mast-mounted filters aspirated at the rate of 18.1 lpm. If the collection efficiency were a constant independent of mass on the filter, these two values would be simply proportional to their corresponding flow rates. Based on the lower yield at the higher flow rate, it was determined that the collection efficiency ϵ is given by

$$\epsilon = \begin{cases} 1 & m_{zn} \leq m_o \\ \exp \left[-\frac{(m_{zn} - m_o)}{m_c} \right] & m_{zn} > m_o \end{cases}, \quad (4.2)$$

where m_o and m_c are characteristic constants determined to be 120 μg and 32 μg , respectively. Thus, the collection efficiency is roughly 100% at loadings less than 120 μg and drops off exponentially for loadings above this value. Substituting Eqn. 4.2 into Eqn. 4.1 and integrating over the duration of the release T , we obtain the following expression for the mean concentration $\bar{C}$.

$$\bar{C}_{zn} = \begin{cases} \frac{m_{zn}}{\dot{V}_o T} & m_{zn} \leq m_o \\ \frac{m_o + m_c \exp \left[\frac{(m_{zn} - m_o)}{m_c} \right]}{\dot{V}_o T} & m_{zn} > m_o \end{cases}, \quad (4.3)$$

The concentrations determined from Eqn. 4.3 are tabulated for each sampler location in Appendix E. Since no significant trend with height above the ground was evident, the four measurements on each mast were averaged to reduce statistical variability. The concentrations measured on the four transects during each of the five

HC tests are plotted in Figs. 14 through 18. The results are similar in nature to those obtained with the fog-oil smoke.

An additional perspective on the quality of the data is provided in Figs. 19 and 20. Figure 19 shows nondimensional crosswind-integrated concentration plotted against nondimensional downwind distance. Figure 20 shows nondimensional plume width versus nondimensional downwind distance. In both cases, the convective scaling suggested by Nieuwstadt (1980) is used. The crosswind-integrated concentration C_y and the plume width σ_y were determined from the pointwise transect measurements by fitting a Gaussian profile to the data. In Figs. 19 and 20, the scaled results are compared with the well-known data from Project Prairie Grass (see Barad, 1956). The agreement is seen to be quite good despite our need to adjust the measured data to correct for filter loading. As reported by Liljegren et al., this scaling analysis also collapses our own fog-oil measurements as well as the field data from Project CONDORS (see Kaimal et al., 1986) and the laboratory data taken by Deardorff and Willis (1975). Thus, the value of the scaling analysis is readily apparent, and the quality of our HC concentration data is comparable to that of the other sets of data available to test dispersion models under convective atmospheric conditions over flat terrain.

5. SUMMARY AND CONCLUSIONS

Five dispersion experiments were conducted under daytime convective conditions in moderately flat terrain at Camp Atterbury, Indiana during November, 1987. The source for each test consisted of 18-20 M5 hexachloroethane (HC) smoke pots burned over a period of between 25 and 47 min. The plume was sampled using 46 sampling masts organized into four transects at distances from 50 to 675 m from the source. The particulate phase of the smoke was collected at four heights (2, 4, 6 and 8 m) on each mast using cellulose membrane filters housed in aspirated cassettes. In addition, twelve samples of the vapor phase were collected using Tenax-filled tubes in series with filter cassettes. Particle size was measured at a single location using a quartz-crystal-microbalance cascade impactor. Meteorological data were collected using a 10-m instrument tower and a 2-m mast upwind of the source.

The filter samples were analyzed by inductively coupled argon plasma atomic emission spectrometry and ion chromatography. All 920 samples collected during the five tests were analyzed for zinc and aluminum. Ten of the most heavily exposed filters were analyzed for 45 elements and 22 additional samples were analyzed for 11

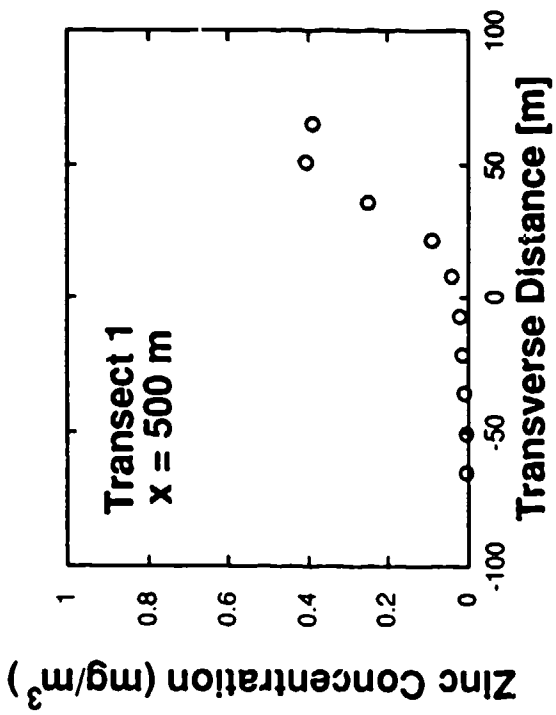
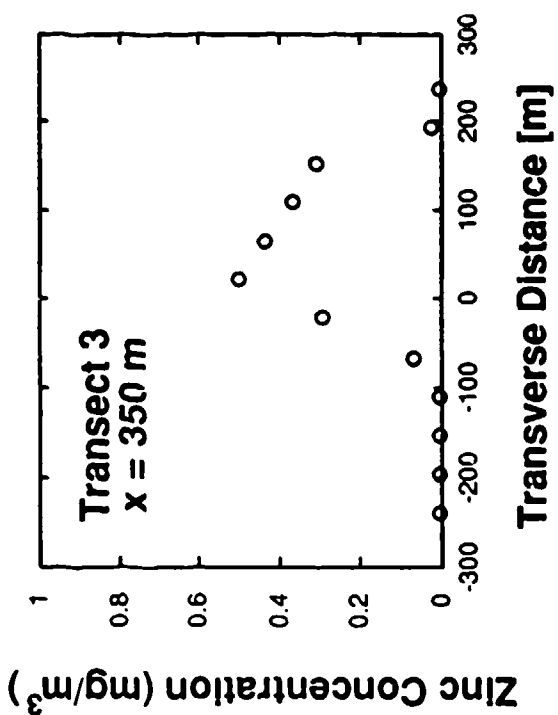
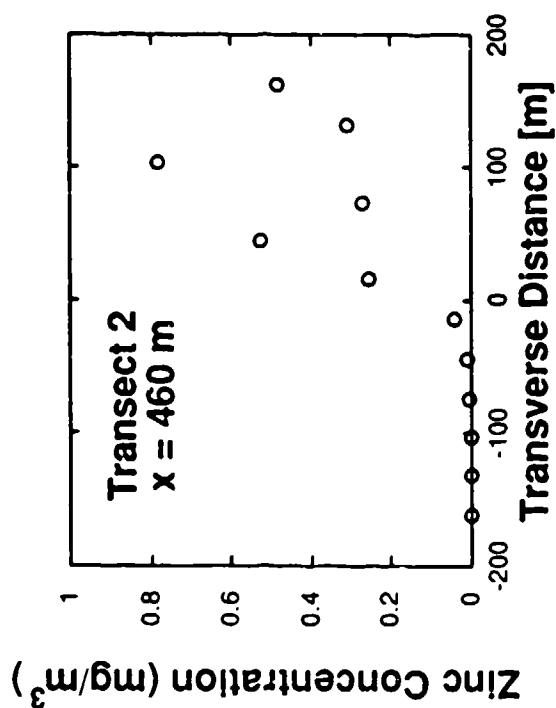
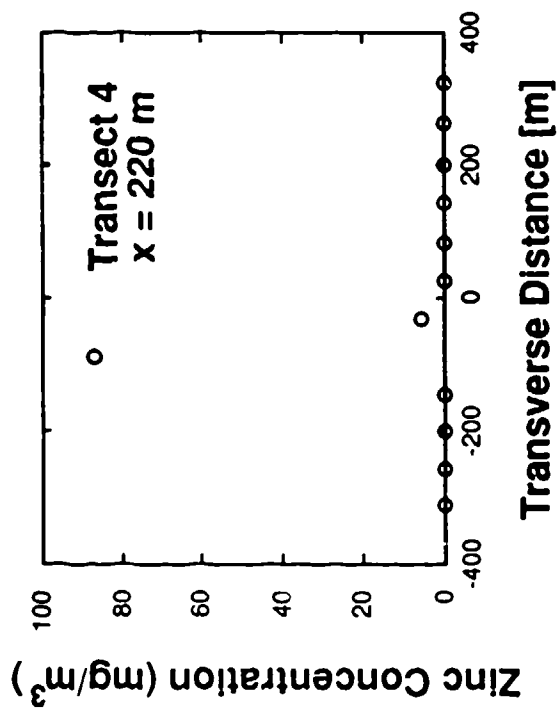


Figure 14. Average zinc concentration data for Test 1109871. Averages are taken over all four sampling heights.

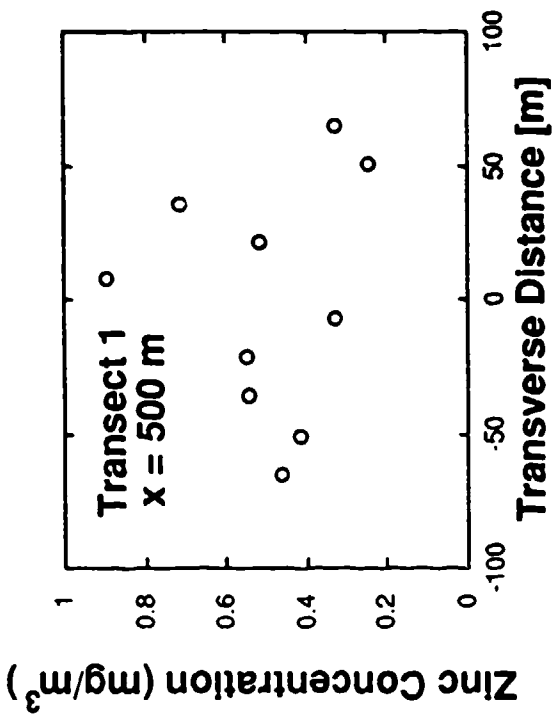
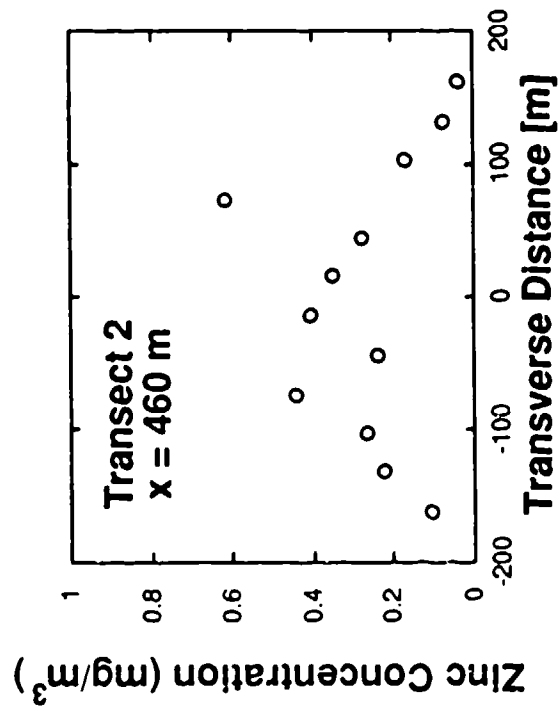
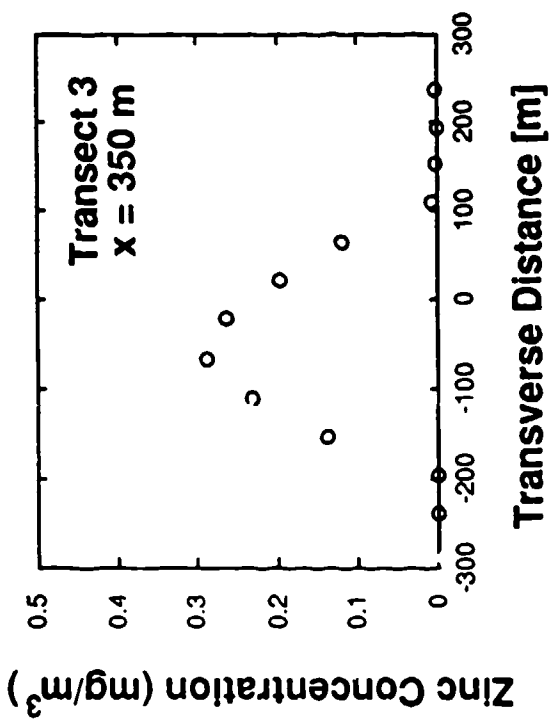
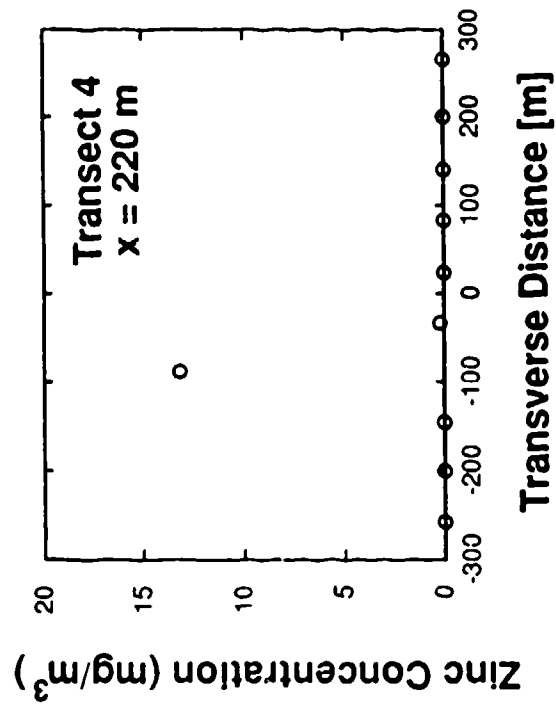


Figure 15. Average zinc concentration data for Test 1110871. Averages are taken over all four sampling heights.

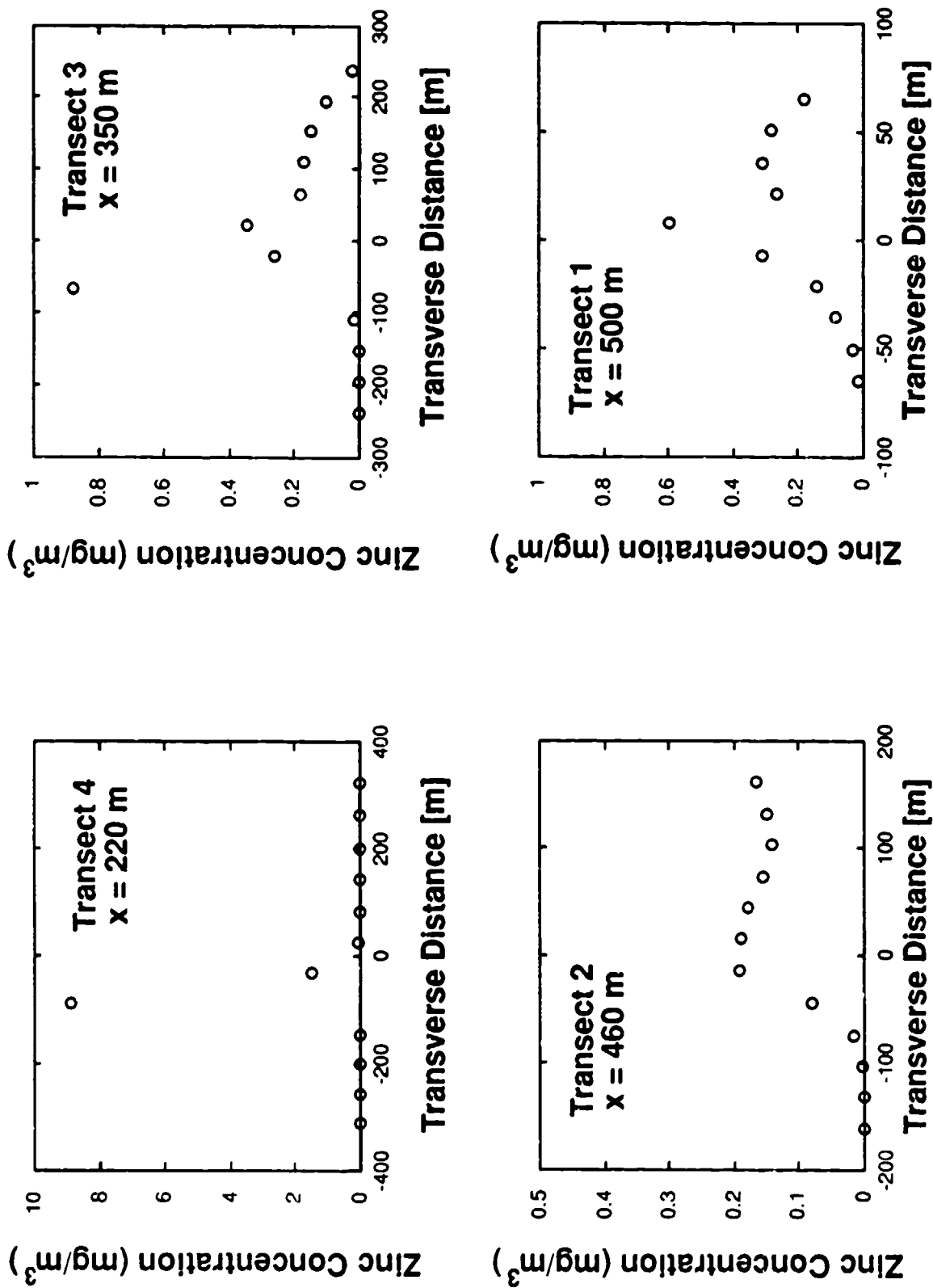


Figure 16. Average zinc concentration data for Test 1110872. Averages are taken over all four sampling heights.

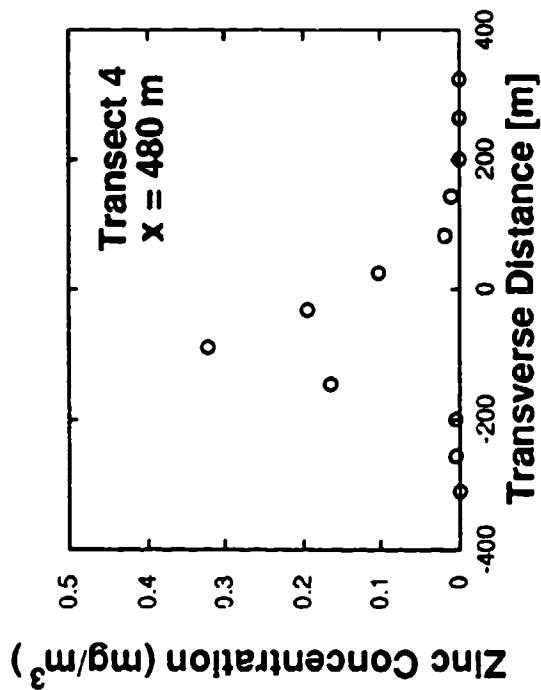
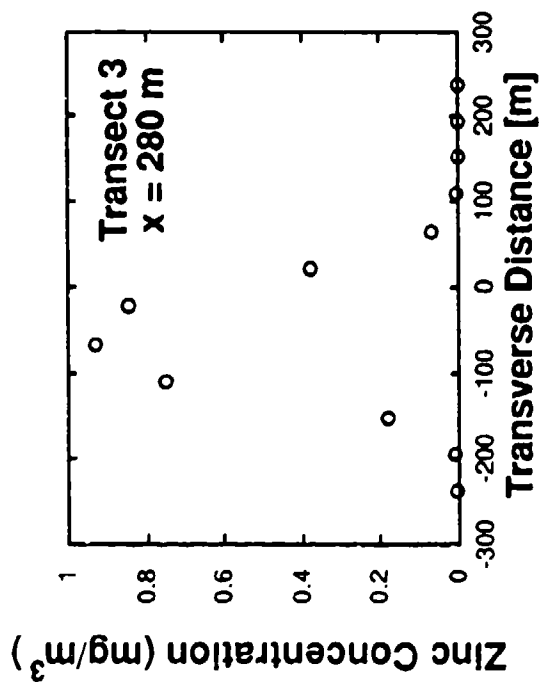
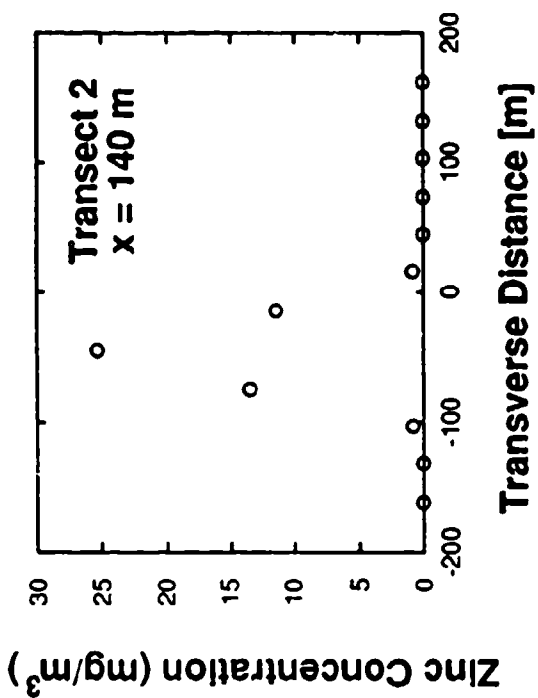
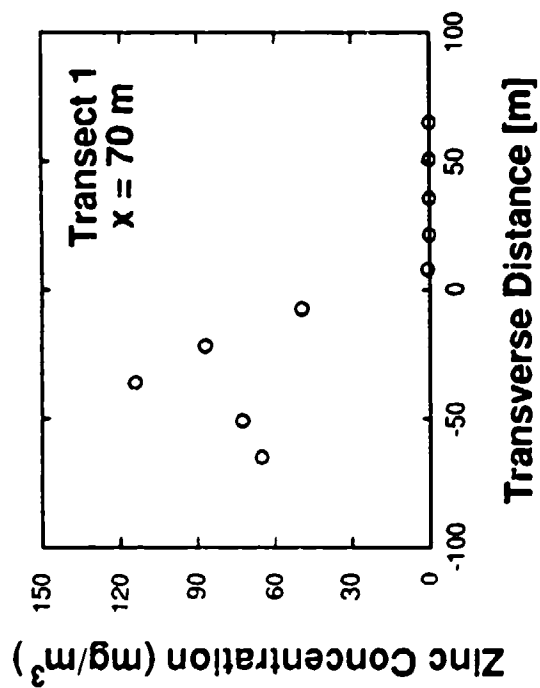


Figure 17. Average zinc concentration data for Test 1112871. Averages are taken over all four sampling heights.

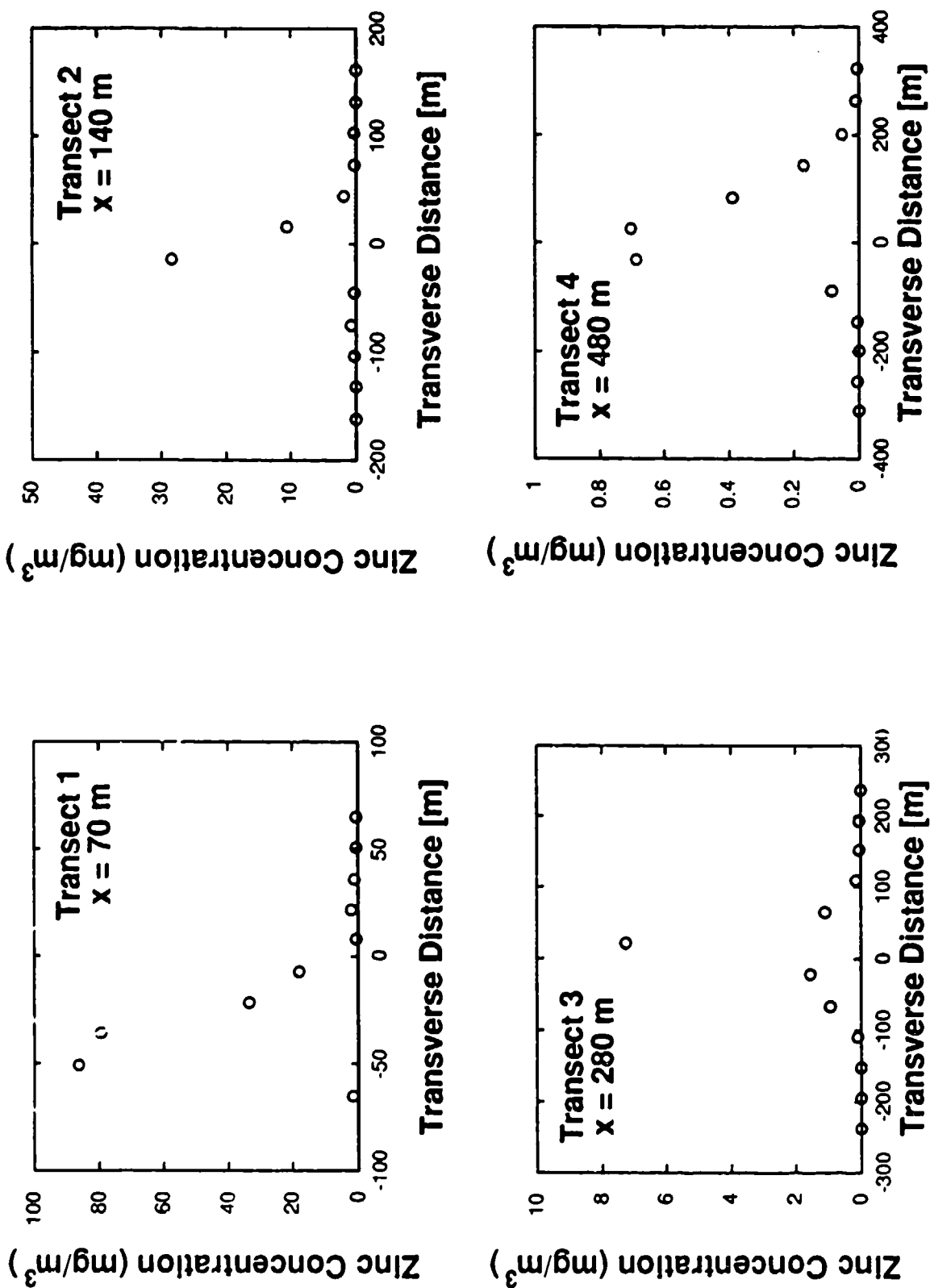


Figure 18. Average zinc concentration data for Test 113871. Averages are taken over all four sampling heights.

Comparison of Airborne Zinc Concentration Data with Data from Project Prairie Grass

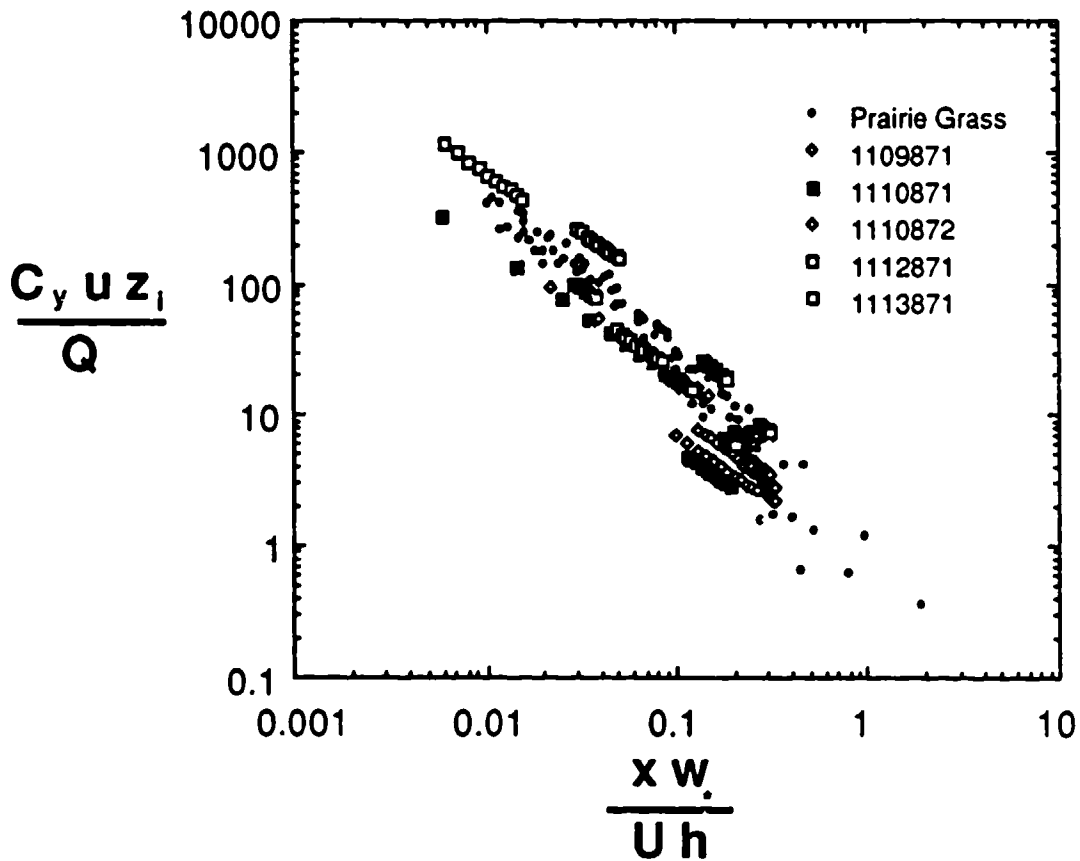


Figure 19. Comparison of airborne zinc concentration data with data from Project Prairie Grass. Comparison is made in terms of nondimensional crosswind-integrated ground-level concentration versus nondimensional downwind distance. Crosswind integrated concentration is determined from pointwise measurements by fitting the transect data to a Gaussian lateral profile.

Comparison of Plume Width Data with Similar Data from Project Prairie Grass

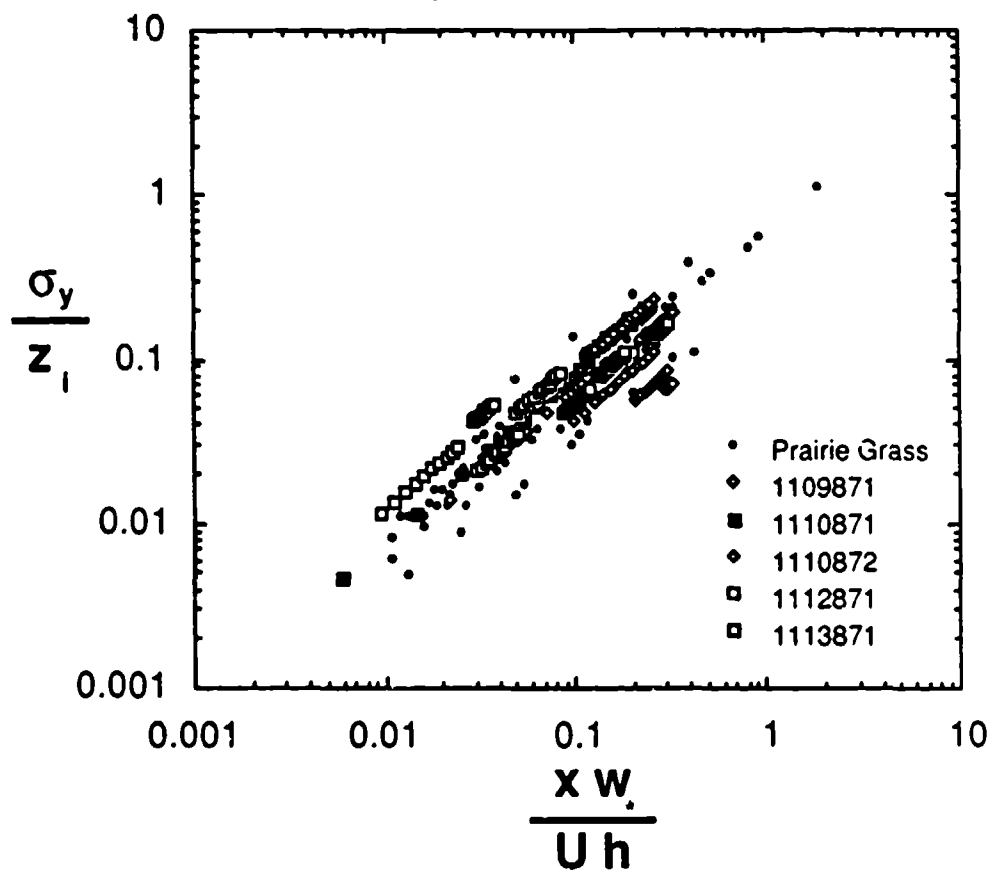


Figure 20. Comparison of plume width data with similar data from Project Prairie Grass. Comparison is made in terms of nondimensional plume width versus nondimensional downwind distance. Plume width is determined from pointwise measurements by fitting the transect data to a Gaussian lateral profile.

elements. The vapor-phase samples were analyzed for four specific chlorinated organic compounds.

Results indicated that the HC smoke has a bimodal particle size distribution with about 5 – 15% of the mass contained in the smaller size range. It is theorized that these particles could be solid aluminum oxide with a geometric mean diameter of about 0.1 μm . This possibility was offered as a potential explanation as to why the filters with a small amount of collected mass showed abnormally low aluminum levels.

The chemical analysis of the samples revealed that the smoke is roughly 90% particulate and 10% vapor by mass. The particulate phase contains zinc, chlorine, aluminum, iron and lead in significant quantities. The presence of iron in rather large amounts was somewhat unexpected, although its existence can be partly attributed to the metal canister which houses the pot material and is partially vaporized as the pot burns. The amount of iron seemed to be larger than could be explained from this source alone, however. Lead, present in rather small amounts, is most likely an impurity which arises in the zinc processing. The amount of chlorine is less than the stoichiometric level required to consume all the zinc as chloride. Therefore, it is probable that some of the zinc and most of the other metals exist in oxide form in the HC particulate. The four targeted organic compounds were found to account for about a third of the vapor phase.

A key point to be stressed is the variability of smoke composition. This variability, seen in all aspects of the chemical analysis, indicates that individual smoke samples may differ greatly from the mean determined in our study. Moreover, factors such as ambient temperature, ambient humidity, wind speed and pot orientation may all affect the HC smoke products, although the examination of these effects lies outside the scope of the present study.

It was discovered that filter loading was a significant problem in collecting the HC particulate phase. A crude analysis of this effect was developed based on results obtained from samples aspirated at widely different rates. The concentration data obtained using the results of this analysis showed good agreement with other dispersion data in nondimensional form. Thus, the corrected concentration data are suitable for model testing in the appropriate context.

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Appendix A. Coordinate Information

This appendix provides detailed coordinate information for the grid used in the HC smoke dispersion trials. Table A.1 gives the coordinates of the meteorological tower and the two release points. Table A.2 gives the coordinates of the sampling masts. All values are given in meters relative to a local origin within the grid.

Table A.1 Coordinates of the meteorological instrument tower and the two release points.

Location	East [m]	North [m]
Meteorological Instrument Tower	316.39	298.43
Release Point Used for Tests 1109871, 1110871 and 1110872	270.3	470.8
Release Point Used for Tests 1112871 and 1113871	-21.1	21.1

Table A.2 Coordinates of the sampling masts.

TRANSECT 1		
Mast Number	East [m]	North [m]
1	-11.7	80.9
2	-1.7	70.6
3	8.6	60.2
4	18.8	50.1
5	28.8	39.8
6	39.4	29.1
7	49.4	19.3
8	59.3	9.2
9	69.7	-1.4
10	79.9	-11.5

TRANSECT 2		
Mast Number	East [m]	North [m]
1	-41.5	188.7
2	-21.3	166.7
3	-2.3	146.1
4	18.0	124.3
5	38.7	102.1
6	59.1	80.0
7	79.0	58.3
8	98.8	36.8
9	118.2	15.6
10	138.0	-5.8
11	157.9	-27.2
12	178.0	-49.0

TRANSECT 3		
Mast Number	East [m]	North [m]
1	0.3	348.2
2	31.3	317.3
3	61.5	287.0
4	91.8	256.7
5	122.6	225.9
6	153.6	194.9
7	184.0	164.5
8	215.1	133.4
9	246.4	102.1
10	276.7	71.8
11	306.7	41.9
12	337.1	11.4

TRANSECT 4		
Mast Number	East [m]	North [m]
1	74.7	543.6
2	113.9	507.9
3	154.5	466.4
4	194.3	427.3
5	235.1	388.3
6	275.5	349.3
7	316.5	308.7
8	357.7	267.3
9	398.8	225.9
10	440.0	184.1
11	485.5	137.4
12	526.3	95.2

Appendix B. Aluminum and Zinc Mass Measurements

This appendix summarizes the raw aluminum and zinc mass measurements for all 920 filter samples which were analyzed. The data are given in 10 tables as follows.

TEST	Table of Aluminum Masses	Table of Zinc Masses
1109871	B.1	B.2
1110871	B.3	B.4
1110872	B.5	B.6
1112871	B.7	B.8
1113871	B.9	B.10

Table B.1 Aluminum mass measurements for Test 1109871.

Test: 1109871
Duration = 25 min.
Flowrate = 18.1 lpm

Total Mass Released = 222.1 kg
Average Release Rate = 148.1 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Aluminum [μg]				Avg. Mass [μg]
		1-m	2-m	4-m	8-m	
1	1	<0.5	<0.5	2	<0.5	2.00
1	2	<0.5	0.8	1	1.4	1.07
1	3	0.8	0.6	0.6	0.9	0.73
1	4	2.6	1.2	<0.5	<0.5	1.90
1	5	2.2	<0.5	2.5	1.5	2.07
1	6	<0.5	<0.5	<0.5	1.3	1.30
1	7	1	2	1	1.1	1.28
1	8	1.3	1.4	1.5	2.4	1.65
1	9	3.5	3.2	2.8	2.8	3.08
1	10	3.5	4.7	2.7	4.1	3.75
2	1	2.9	0.6	1.6	<0.5	1.70
2	2	0.7	0.6	2	7.1	2.60
2	3	1.3	0.5	1.5	<0.5	1.10
2	4	<0.5	0.7	0.7	1.5	0.97
2	5	<0.5	1.1	0.6	<0.5	0.85
2	6	0.7	1.3	0.9	1	0.98
2	7	3.4	2.7	2	1.6	2.43
2	8	4.5	4.8	2.8	3.6	3.93
2	9	10.3	9.1	4.7	8.9	8.25
2	10	6.3	5.4	6.5	3.6	5.45
2	11	8.7	11.2	4.7	9	8.40
2	12	8.8	10.1	7.7	7.9	8.63
3	1	<0.5	<0.5	<0.5	0.6	0.60
3	2	1	0.6	0.8	1.6	1.00
3	3	<0.5	1.7	0.7	1.1	1.17
3	4	0.7	0.5	0.5	0.7	0.60
3	5	0.6	0.6	0.6	0.9	0.68
3	6	9.6	6.7	6.8	7.7	7.70
3	7	20	8.2	19	9.8	14.25
3	8	14.1	5.6	6	8.6	8.58
3	9	5.6	8.1	4.5	4	5.55
3	10	5.1	2.4	2.6	2.2	3.08
3	11	5.7	0.9	0.8	1	2.10
3	12	0.8	1.3	0.8	1.4	1.08
4	1	0.8	0.9	1.4	0.5	0.90
4	2	0.9	0.9	0.9	<0.5	0.90
4	3	1.1	0.5	0.5	0.7	0.70
4	4	0.6	1.3	0.6	<0.5	0.83
4	5	25.1	32.3	56.9	35.3	27.40
4	6	42.7	40.2	34.5		39.13
4	7	0.7	0.8	1.1	1.3	0.98
4	8	0.9	1.2	<0.5	<0.5	1.05
4	9	1.1	0.8	0.8	1.3	1.00
4	10	0.9	1.1	0.7	<0.5	0.90
4	11	0.9	0.8	1	1	0.93
4	12	0.6	0.8	0.8	0.8	0.75

Table B.2 Zinc mass measurements for Test 1109871.

Test: 1109871
 Duration = 25 min.
 Flowrate = 18.1 lpm

Total Mass Released = 222.1 kg
 Average Release Rate = 148.1 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Zinc (μ g)				Avg. Mass [μ g]
		1-m	2-m	4-m	8-m	
1	1	2.26	2.17	1.98	1.46	1.97
1	2	2.7	2.93	2.88	2.35	2.72
1	3	4.66	5.2	5.37	4.01	4.81
1	4	6.7	6.7	7.79	6.48	6.92
1	5	8.46	7.61	7.76	10.12	8.49
1	6	18.24	20.22	16.73	16.07	17.82
1	7	37.19	38.02	43.48	41.97	40.17
1	8	118.1	103.32	110.63	121.48	113.38
1	9	171.7	149.15	154.05	145.98	155.22
1	10	179.71	139.38	124.73	168.23	153.01
2	1	0.36	0.24	0.36	0.46	0.36
2	2	0.25	0.31	0.51	0.45	0.38
2	3	0.4	0.21	0.22	0.26	0.27
2	4	2.22	2.59	2.9	2.16	2.47
2	5	3.75	3.71	4.46	3.87	3.95
2	6	20.93	18.31	18.83	14.99	18.27
2	7	132.58	104.55	124.43	96.4	114.49
2	8	214.73	149.03	159.15	157.7	170.15
2	9	120.64	127.81	114.55	124.06	121.77
2	10	218.12	188.78	188.04	157.72	188.17
2	11	167.16	128.78	138.7	105.05	134.92
2	12	211.58	149.4	138.09	162.62	165.42
3	1	0.47	0.37	1.32	0.31	0.62
3	2	0.46	0.33	1.29	0.37	0.61
3	3	0.65	1.52	0.48	0.4	0.76
3	4	1.4	1.74	1.98	2.49	1.90
3	5	23.97	26.4	27.52	41.88	29.94
3	6	119.99	166.32	110.72	123.71	130.19
3	7	157.45	189.32	161.83	160.16	167.19
3	8	140.27	152.04	169.9	177.22	159.86
3	9	185.64	157.89	132.47	120.56	149.14
3	10	134.51	170.07	105.72	132.05	135.59
3	11	10.45	11.8	9.45	16.15	11.96
3	12	0.46	0.6	0.61	0.71	0.60
4	1	0.29	0.58	0.59	0.42	0.47
4	2	0.28	0.3	0.34	0.61	0.38
4	3	0.48	0.3	0.11	0.45	0.34
4	4	0.46	0.26	0.46	0.28	0.37
4	5	298.13	338.61	429.11	326.1	347.99
4	6	243.61	269.29	269.38		260.76
4	7	1.23	3.17	6.35	16.3	6.76
4	8	0.72	0.34	0.24	0.33	0.41
4	9	0.8	0.32	0.24	0.65	0.50
4	10	0.39	0.24	0.33	0.35	0.33
4	11	0.49	0.34	0.25	0.23	0.33
4	12	0.31	0.27	0.21	0.34	0.28

Table B.3 Aluminum mass measurements for Test 1110871.

Test: 1110871
Duration = 36.5 min.
Flowrate = 18.1 lpm

Total Mass Released = 229.3 kg
Average Release Rate = 104.7 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Aluminum [μg]				Avg. Mass [μg]
		1-m	2-m	4-m	8-m	
1	1	5.9	6.3	4.5	5	5.43
1	2	4.8	4.4	6.1	5	5.08
1	3	6.8	5.8	6.3	5.6	6.13
1	4	7.6	6.5	6.2	5.3	6.40
1	5	6	5.2	6.2	5.8	5.80
1	6	7.8	15.4	<0.5	5.1	9.43
1	7	7.4	6.5	6.1	6.1	6.53
1	8	5.8	6.5	5.5	3.5	5.33
1	9	7.1	3.3	3.2	4	4.40
1	10		6.2	4.4	4.9	5.17
2	1	0.5	0.7	1.9	2	1.28
2	2	2.6	3.6	4.2	4	3.60
2	3	4.6	3	6	5.3	4.73
2	4	4.1	6.6	6.7	5.8	5.80
2	5	4	3.1	6.6	7.9	5.40
2	6	6.6	4.6	6.3	7.3	6.20
2	7	2.9	5.2	6.6	7.1	5.45
2	8	5.4	3.9	6.1	4.4	4.95
2	9	2.7	0.9	4.9	4.5	3.25
2	10	3.2	1.5	3.8	2.7	2.80
2	11	0.9	1.8	1.9	2.4	1.75
2	12	1.2	1	2.8	2.9	1.98
3	1	0.8	0.6	0.8	<0.5	0.73
3	2	<0.5	<0.5	1.2	<0.5	1.20
3	3	2	1.3	1.4	1.8	1.63
3	4	8.7	7.2	9.7	7.3	8.23
3	5	13.7	12.3	12.3	9.2	11.88
3	6	9.6	8.7	7.8	6.2	8.08
3	7	6.7	8.7	2.3	5.3	5.75
3	8	2	1.9	0.6	10.1	3.65
3	9	<0.5	0.6	0.8	0.9	0.77
3	10	1	0.7	0.8	0.8	0.83
3	11	0.9	0.6	<0.5	0.7	0.73
3	12	0.7	<0.5	1.2	0.8	0.90
4	1	0.6	1	<0.5	0.7	0.77
4	2	0.8	<0.5	<0.5	<0.5	0.80
4	3	0.6	0.9	0.9	<0.5	0.80
4	4	0.8	0.8	0.7	<0.5	0.77
4	5	18.9	32.1	17.7	29.5	24.55
4	6	4.4	3.1	2.5	2.7	3.18
4	7	0.6	0.9	3	<0.5	1.50
4	8	1	0.7	0.7	1	0.85
4	9	0.8	1.3	1.1	0.5	0.93
4	10	1	0.9	<0.5		0.95
4	11	<0.5	1.1	0.7	<0.5	0.90
4	12	0.7	1.2	0.6	0.6	0.78

Table B.4 Zinc mass measurements for Test 1110871.

Test: 1109871
 Duration = 36.5 min.
 Flowrate = 18.1 lpm

Total Mass Released = 229.3 kg
 Average Release Rate = 104.7 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Zinc [µg]				Avg. Mass [µg]
		1-m	2-m	4-m	8-m	
1	1	183.04	187.88	179.99	176.37	181.82
1	2	200.43	148.55	154.91	202.26	176.54
1	3	163.68	216.04	204.03	171.08	188.71
1	4	220.64	199.62	140.46	196.29	189.25
1	5	187.63	193.42	147.27	130.97	164.82
1	6	197.35	235.21	181.59	220.15	208.58
1	7	221.88	215.84	171.8	137.16	186.67
1	8	209.6	204.33	189.61	195.61	199.79
1	9	127.94	116.65	181.85	162.28	147.18
1	10		195.41	117.29	181.68	164.79
2	1	63.2	71.56	70.77	69.35	68.72
2	2	120.76	116.94	187.28	132.35	139.33
2	3	180.53	132.76	139.79	154.4	151.87
2	4	146.28	147.48	206.27	218.35	179.60
2	5	160.1	136.81	156.73	125.9	144.89
2	6	170.5	148.26	232.8	149.45	175.25
2	7	193.93	178.75	109.75	192.07	168.63
2	8	180.54	179.16	138.05	119.83	154.40
2	9	202.91	0.39	175.53	203.61	145.61
2	10	112.95	109.51	114.21	104.36	110.26
2	11	41.41	52.43	48.1	53.83	48.94
2	12	23.59	25.24	24.36	24.57	24.44
3	1	0.58	0.3	0.35	0.35	0.40
3	2	0.35	0.29	0.6	0.52	0.44
3	3	95.12	85.25	101.99	84.41	91.69
3	4	133.92	143.89	182.61	110.33	142.69
3	5	145.01	160.32	163.42	162.16	157.73
3	6	156.41	160.3	167.66	124.57	152.24
3	7	137.94	148.35	90.42	140.95	129.42
3	8	73.29	65.99	7.01	172.4	79.67
3	9	5.91	6.78	1.12	6.15	4.99
3	10	0.69	0.66	0.36	1.9	0.90
3	11	0.29	0.18	0.38	0.3	0.29
3	12	0.39	0.18	1.27	0.43	0.57
4	1	0.53	0.36	0.27	0.69	0.46
4	2	0.4	0.27	0.35	0.25	0.32
4	3	0.35	0.37	1.52	0.24	0.62
4	4	1.59	1.12	1	9.08	3.20
4	5	217.07	221.8	380.79	379.12	299.70
4	6	155.15	145.79	125.8	124.31	137.76
4	7	0.87	0.27	0.32	0.29	0.44
4	8	0.41	0.33	0.24	0.89	0.47
4	9	0.66	0.38	0.3	0.26	0.40
4	10	0.44	0.38	0.31		0.38
4	11	0.32	0.32	0.74	0.31	0.42
4	12	0.21	0.63	0.45	0.11	0.35

Table B.5 Aluminum mass measurements for Test 1110872.

Test: 1110872
Duration = 47.3 min.
Flowrate = 18.1 lpm

Total Mass Released = 219.5 kg
Average Release Rate = 77.3 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Aluminum [μg]				Avg. Mass [μg]
		1-m	2-m	4-m	8-m	
1	1	1.8	0.6	0.8	1	1.05
1	2	1.6	1.2	1.4	1.1	1.32
1	3	2.7	1.6	1.6	1.9	1.95
1	4	3.7	3.3	2.5	3.6	3.28
1	5	4.4	3.5	3.3	4.4	3.90
1	6	6.3	5.7	5.8	5.9	5.93
1	7	4.8	4.2	6.9	6.8	5.68
1	8	8.1	7.8	6.7	6.2	7.20
1	9	7.3	7.6	5.2	6.6	6.67
1	10	6.2	9	6.8	5.3	6.83
2	1	1.7	1.4	0.8	1.1	1.25
2	2	0.6	1.1	1.4	2.2	1.33
2	3	0.7	1.3	0.7	1.1	0.95
2	4	0.9	1.4	2.1	1.5	1.48
2	5	1.4	2.5		2.2	2.03
2	6	5.7	5.9	5.5	6.1	5.80
2	7	9.6	7.4	8.5	8	8.38
2	8	10	10.7	10.2	6.4	9.33
2	9	8.8	9.2	10.1	7.3	8.85
2	10	5	4.6	5.3	4.6	4.88
2	11	4.4	6.7	6.4	3.3	5.20
2	12	5.7	5.3	6.6	5.5	5.78
3	1	<0.5	<0.5	<0.5	0.7	0.70
3	2	<0.5	<0.5	<0.5	<0.5	0.00
3	3	<0.5	<0.5	<0.5	<0.5	0.00
3	4	<0.5	<0.5	0.6	0.6	0.60
3	5	4.9	6.2	7.3	6.2	6.15
3	6	13.1	16.1	11.7	14.7	13.90
3	7	15.7		14.5	10.4	13.53
3	8		11.3	10.4	10.1	10.60
3	9	4.5	3.7	4.3	4.8	4.33
3	10	2.6	1.6	1.8	2.6	2.15
3	11	1.2	1	1	0.9	1.03
3	12	<0.5	<0.5	<0.5	<0.5	0.00
4	1	<0.5	<0.5	<0.5	<0.5	0.00
4	2	<0.5	<0.5	<0.5	<0.5	0.00
4	3	<0.5	<0.5	<0.5	<0.5	0.00
4	4	<0.5	<0.5	<0.5	<0.5	0.00
4	5	28.6	23	18.6	19.9	22.53
4	6		22.8	14	15.6	17.47
4	7	<0.5	<0.5	<0.5	<0.5	0.00
4	8	<0.5	<0.5	<0.5	<0.5	0.00
4	9	<0.5	<0.5	<0.5	<0.5	0.00
4	10	<0.5	<0.5	<0.5	<0.5	0.00
4	11	<0.5	<0.5	<0.5	<0.5	0.00
4	12	<0.5	<0.5	<0.5	<0.5	0.00

Table B.6 Zinc mass measurements for Test 1110872.

Test: 1110872

Duration = 47.3 min.

Flowrate = 18.1 lpm

Total Mass Released = 219.5 kg

Average Release Rate = 77.3 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Zinc [µg]				Avg. Mass [µg]
		1-m	2-m	4-m	8-m	
1	1	11.07	10.76	11.83	11.09	11.19
1	2	20.82	29.18	29.49	24.97	26.12
1	3	67.87	66.7	78.87	71.97	71.35
1	4	115.4	129.57	120.94	120.92	121.71
1	5	167.28	178.77	164.61	187.36	174.51
1	6	211.26	198.13	196.29	205.66	202.84
1	7	124.4	168.16	153.14	222.86	167.14
1	8	129.4	234.4	174.74	161.65	175.05
1	9	126.11	204.79	209.2	139.99	170.02
1	10	156.46	124.89	163.32	126.82	142.87
2	1	0.19	0.22	0.18	0.18	0.19
2	2	0.35	0.27	0.34	0.78	0.44
2	3	1.2	0.84	0.9	0.94	0.97
2	4	15.32	15.39	12.61	12.99	14.08
2	5	72.19	78.58		50.24	67.00
2	6	175.67	122.89	134.61	223.1	164.07
2	7	249.14	152.42	127.24	114.29	160.77
2	8	182.93	150.02	150.34	125.53	152.21
2	9	124.29	134.32	143.95	125.34	131.98
2	10	141.12	114.5	103.33	119.19	119.54
2	11	121.08	119.5	158.27	107.64	126.62
2	12	119.58	140.32	177.88	126.47	141.06
3	1	0.3	0.42	0.28	0.39	0.35
3	2	0.28	0.25	0.23	0.4	0.29
3	3	0.33	0.25	0.26	0.34	0.30
3	4	12.05	12.92	13.82	14	13.20
3	5	160.79	223.28	244.36	241.5	217.48
3	6	154.95	188.96	151.98	169.49	166.35
3	7	208.73		177.69	153.83	180.08
3	8		140.01	150.82	142.1	144.31
3	9	129.86	139.95	146.92	140.14	139.22
3	10	127.95	158.4	108.88	110.17	126.35
3	11	82.03	84.42	84.18	90.86	85.37
3	12	15.39	15.93	17.75	17.65	16.68
4	1	0.53	0.2	0.16	0.21	0.28
4	2	0.13	0.17	0.22	0.21	0.18
4	3	0.21	0.49	0.11	0.22	0.26
4	4	0.31	0.22	0.19	0.18	0.23
4	5	342.33	255.94	272.86	309.82	295.24
4	6		283.83	228.96	192.44	235.08
4	7	15.92	15.69	9.48	10.41	12.88
4	8	0.21	0.17	0.27	0.23	0.22
4	9	0.23	0.27	0.5	0.21	0.30
4	10	0.74	0.35	0.16	0.31	0.39
4	11	0.17	0.42	0.19	0.18	0.24
4	12	0.46	0.32	0.17	0.22	0.29

Table B.7 Aluminum mass measurements for Test 1112871.

Test: 1112871
Duration = 45.7 min.
Flowrate = 18.1 lpm

Total Mass Released = 218.5 kg
Average Release Rate = 79.7 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Aluminum [μg]				Avg. Mass [μg]
		1-m	2-m	4-m	8-m	
1	1	31.1	31.6	27.3	33.6	30.90
1	2	27	18.3	37	33	28.83
1	3	28	24.7	44.5	46.3	35.88
1	4	31.1	37.5	30.3	36.2	33.78
1	5	33.1	24.8	28.6	28.1	28.65
1	6	4.7	5.1	5.3	4.1	4.80
1	7	<0.5	0.6	<0.5	<0.5	0.60
1	8	<0.5	<0.5	<0.5	<0.5	0.00
1	9	<0.5	<0.5	<0.5	<0.5	0.00
1	10	<0.5	<0.5	<0.5	<0.5	0.00
2	1	<0.5	<0.5	<0.5	<0.5	0.00
2	2	1.9	<0.5	<0.5	<0.5	1.90
2	3	4.1	6.9	7.9	8.6	6.88
2	4	31.4	25	23.7	26.9	26.75
2	5	29.3	27.6	33.2	28	29.53
2	6	26.9	31	31.8	26.5	29.05
2	7	6	8	5.7	6.7	6.10
2	8	<0.5	1.3	<0.5	<0.5	1.30
2	9	<0.5	<0.5	<0.5	0.8	0.80
2	10	1.6	1.1	0.6	<0.5	1.10
2	11	<0.5	0.7	0.8	0.6	0.70
2	12	<0.5	<0.5	<0.5	<0.5	0.00
3	1	1	<0.5	<0.5	<0.5	1.00
3	2	0.8	<0.5	<0.5	<0.5	0.80
3	3	2.8	2.6	3	5.7	3.53
3	4	6.8	7.7	6.9	7.3	7.18
3	5	11.7	10.9	3.9	9.3	8.95
3	6	10.1	9.2	8.4	8.1	8.95
3	7	5.3	2.4	5.3	4.2	4.30
3	8	0.6	1.4	1	1.1	1.03
3	9	0.8	1	<0.5	<0.5	0.90
3	10	1.4	0.5	<0.5	<0.5	0.95
3	11	0.6	0.6	0.5	1.2	0.73
3	12	1	1.3	<0.5	<0.5	1.15
4	1	0.9	0.9	1.1	0.8	0.93
4	2	1.1	1.3	1.2	0.7	1.08
4	3	<0.5	<0.5	0.7	0.5	0.60
4	4	2.9	2.5	3.4	3.1	2.98
4	5	5.5	4.6	3.9	4.4	4.60
4	6	3.7	2.9	3	3.3	3.23
4	7	1.8	2.3	2.7	2.1	2.23
4	8	1.4	1.5	1.1	1.1	1.28
4	9	1.3	1.2	<0.5	0.9	1.13
4	10	1.3	0.6	0.5	0.6	0.75
4	11	1	0.8	0.8	0.7	0.83
4	12	0.8	0.6	0.6	0.8	0.70

Table B.8 Zinc mass measurements for Test 1112871.

Test: 1112871
 Duration = 45.7 min.
 Flowrate = 18.1 lpm

Total Mass Released = 218.5 kg
 Average Release Rate = 79.7 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Zinc [µg]				Avg. Mass [µg]
		1-m	2-m	4-m	8-m	
1	1	348.47	308.56	376.31	400.15	358.37
1	2	338.36	345.5	431.42	333.32	361.65
1	3	219.27	226.45	530.88	528.13	376.18
1	4	386.43	288.7	289.44	504.88	367.36
1	5	341.93	249.1	395.55	410.76	349.34
1	6	165.39	201.57	183.19	161.51	177.92
1	7	34.26	26.34	24.08	9.55	23.56
1	8	0.89	0.71	1.27	0.93	0.95
1	9	0.31	<0.05	0.65	0.63	0.53
1	10	0.2	0.29	0.24	0.23	0.24
2	1	0.33	0.37	0.3	0.35	0.34
2	2	27.13	23.68	32.73	28.59	28.03
2	3	242.31	186.96	175.28	252.94	214.37
2	4	468.65	241.33	250.1	269.97	307.51
2	5	269.58	385.87	370.38	285.33	327.79
2	6	268.95	375.22	352.71	212.39	302.32
2	7	224.7	190	200.01	246.07	215.20
2	8	12.52	12.71	16	17.29	14.63
2	9	0.43	0.52	0.35	0.76	0.52
2	10	0.68	0.35	0.5	0.37	0.48
2	11	1.09	1.06	0.28	0.28	0.68
2	12	0.74	0.22	0.36	0.21	0.38
3	1	0.9	0.83	1.41	1.16	1.08
3	2	4.82	4.5	4.56	8.19	5.52
3	3	136.25	136.54	144.97	144.68	140.61
3	4	221.85	203.21	232.97	183.29	210.33
3	5	288.52	212.97	107.6	264.16	218.31
3	6	229.29	208.54	199.35	222.72	214.98
3	7	168.35	188.58	183.53	188.97	182.36
3	8	53.93	48.48	57.06	73.04	58.13
3	9	1.48	1.67	1.34	1.32	1.45
3	10	0.52	0.54	0.2	0.27	0.38
3	11	0.21	0.29	0.69	0.24	0.36
3	12	0.22	0.59	0.35	0.34	0.38
4	1	0.36	0.34	0.31	0.57	0.40
4	2	3.87	4.23	3.7	4.03	3.96
4	3	2.83	3.32	3.04	2.2	2.85
4	4	125.52	147.69	125.84	132.28	132.83
4	5	171.99	181.04	164.28	184.64	175.49
4	6	152.88	137.08	142.32	155.31	146.90
4	7	93.07	82.46	84.09	81.82	85.36
4	8	15.13	18.41	14.87	15.26	15.92
4	9	7.65	9.4	8.04	10.25	8.84
4	10	0.33	0.34	0.28	0.35	0.33
4	11	1.19	0.27	0.28	0.17	0.48
4	12	0.28	0.18	0.19	0.29	0.24

Table B.9 Aluminum mass measurements for Test 1113871.

Test: 1113871

Duration = 43 min.

Flowrate = 10.8 lpm (Transect 1)

Flowrate = 18.1 lpm (Transect 2, 3 and 4)

Total Mass Released = 202.0 kg

Average Release Rate = 78.3 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Aluminum [μg]				Avg. Mass [μg]
		1-m	2-m	4-m	8-m	
1	1	7.1	6.8		5.4	6.43
1	2	29	28.7	27.4	25.5	27.65
1	3	17.6	27.3	33.9	21.9	25.18
1	4	23.2	22.9	24.1	26.8	24.25
1	5	24.5	22	25.4	26.3	24.55
1	6	17.2	12.3	12.4	10.4	13.08
1	7	7.1	7.3	7.7	8.7	7.70
1	8	7	5.5	6.9	3.7	5.78
1	9	2.7	5.1	3.1	2.9	3.45
1	10	4.7	1.6	2.6	2.6	2.88
2	1	0.6	0.9	0.9	2.6	1.25
2	2	0.9	1.1	0.8	<0.5	0.93
2	3	2.6	1.1	0.9	0.9	1.38
2	4	10.3	10.6	10	7.9	9.70
2	5	10.2	11.5	11.2	9.6	10.63
2	6	9.2	30.7	23.4	25.8	22.28
2	7	11.8	23.3	27.8	20.3	20.80
2	8	7.4	9.3	9.8	6.1	8.15
2	9	2.7	2.2	2.9	2.3	2.53
2	10	1.9	1.8	2.2	1.5	1.85
2	11	0.7	1.1	1.1	1.5	1.10
2	12	0.9	0.8	0.9	1	0.90
3	1	1.2	0.8	6	1	2.25
3	2	1.4	0.8	0.7	0.8	0.93
3	3	0.8	1	0.7	1.7	1.05
3	4	1.9	3.4	1.7	1.8	2.20
3	5	5.8	6.5	7.6	7	6.73
3	6	10.1	8.7	9.2	11.7	9.93
3	7	12.8	11.1	18.6	8.3	12.70
3	8	9.3	7.7	8.3	7.7	8.25
3	9	2.5	2.7	2.6	4.8	3.15
3	10	0.9	1.5	1.1	1.5	1.25
3	11	1.5	1.4	3.1	1.2	1.80
3	12	0.7	1	1.3	1.2	1.05
4	1	0.7	0.7	0.9	0.5	0.70
4	2	0.9	1.3	1.1	<0.5	1.10
4	3	<0.5	<0.5	<0.5	0.8	0.80
4	4	<0.5	0.8	0.6	0.6	0.67
4	5	1.8	1.2	1.1	2	1.53
4	6	4.2	3.8	4	3.4	3.85
4	7	4.5	4.6	4.7	4	4.45
4	8	4.5	4.6	3.7	3.2	4.00
4	9	3.1	3.8	3.1	3.4	3.35
4	10	2.5	1.4	1.3	1.5	1.68
4	11	1.1	0.6	1.1	1	0.95
4	12	0.7	1.4	0.6	0.8	0.88

Table B.10 Zinc mass measurements for Test 1113871.

Test: 1113871

Duration = 43 min.

Flowrate = 10.8 lpm (Transect 1)

Flowrate = 18.1 lpm (Transects 2, 3 and 4)

Total Mass Released = 202.0 kg

Average Release Rate = 78.3 g/s

TRANSECT NUMBER	MAST NUMBER	Mass of Zinc [μg]				Avg. Mass [μg]
		1-m	2-m	4-m	8-m	
1	1	214.8	240.02		193.88	216.23
1	2	377.62	352.73	435.15	228.82	348.58
1	3	250.56	403.01	386.26	343.33	345.79
1	4	226.86	255.13	343.05	446.72	317.94
1	5	344.71	305.43	241.72	299.39	297.81
1	6	167.47	175.66	156.65	178.45	169.56
1	7	235.02	221.39	212.67	218.58	221.92
1	8	226.85	197.37	202.5	134.67	190.35
1	9	97.94	89.95	109.55	99.7	99.29
1	10	52.53	43.62	64	86.56	61.68
2	1	0.55	0.28	0.18	0.31	0.33
2	2	2.43	0.37	0.24	0.2	0.81
2	3	11.18	10.2	10.82	8.74	10.24
2	4	229.56	218.96	197.9	157.02	200.86
2	5	170.25	188.9	150.97	153.85	165.99
2	6	284.52	455.55	281.71	297.07	329.71
2	7	238.28	288.63	368.91	293.33	297.29
2	8	208.09	244.33	236.57	254.83	235.96
2	9	92.65	93.76	93.13	62.65	85.55
2	10	46.12	49.81	60.7	60.98	54.40
2	11	10.53	7.69	5.53	10.27	8.51
2	12	1.32	0.69	0.46	0.31	0.70
3	1	0.82	0.25	0.86	0.4	0.58
3	2	1.17	0.3	0.49	0.41	0.59
3	3	0.76	1.11	1.14	0.51	0.88
3	4	57.58	62.94	58.5	72.06	62.77
3	5	211.81	240.53	202.54	206.74	215.41
3	6	243.01	254.71	194.64	240.85	233.30
3	7	268	210.2	381.86	281.53	285.40
3	8	246.84	202.29	241.52	198.66	222.33
3	9	118.49	131.61	114.86	113.39	119.59
3	10	22.84	21.74	17.68	16.76	19.76
3	11	10.37	11.53	9.47	14.3	11.42
3	12	0.93	0.53	0.34	0.35	0.54
4	1	0.26	0.59	0.72	0.48	0.51
4	2	1.19	0.88	1.47	0.67	1.05
4	3	0.27	0.5	0.62	0.63	0.51
4	4	0.76	1.19	1.15	1.57	1.17
4	5	75.45	60.66	60.25	71.33	66.92
4	6	188.84	208.22	199.46	222.5	204.76
4	7	214.06	211.37	188.93	208.27	205.66
4	8	209.97	186.39	168.32	159.82	181.13
4	9	141.16	132.39	129.15	110.92	128.41
4	10	44.97	41.88	34.71	33.88	38.86
4	11	6.3	6.85	8.27	6.49	6.98
4	12	1.82	2.13	1.79	1.83	1.89

Appendix C. Elemental Analysis of Selected Samples

This appendix presents results of the detailed analysis carried out on 32 selected filter samples. Table C.1 presents the results of an 11-element analysis of 22 samples. Table C.2 presents the results of a 45-element analysis of 10 samples. In both cases, anion chromatography was used for 5 elements (bromine, chlorine, iodine, nitrogen and sulfur) and inductively coupled argon plasma atomic emission spectroscopy was used for the remaining elements.

Table C.1 Analysis of 22 selected filter samples for 11 elements.

Determined by Anion Chromatography										Analyzed by ICAP-AES					
Test D	Transect Number	Mast Number	Height [m]	Bromide mass (µg)	Chloride mass (µg)	Iodide mass (µg)	Nitrate mass (µg)	Sulfate mass (µg)	Al mass (µg)	As mass (µg)	Cd mass (µg)	Hg mass (µg)	Pb mass (µg)	Zn mass (µg)	
1110871	4	5	8	<1	340	<3	8	6	29.5	0.037	0.38	<0.05	13.2	379.12	
1112871	1	4	6	<1	490	<3	8	<1	36.2	0.028	0.54	<0.05	13.2	504.88	
1112871	2	5	2	<1	380	<3	8	<1	27.6	0.008	0.41	<0.05	7.2	385.87	
1113871	1	5	6	<1	370	<3	7	<1	32.1	0.037	0.52	<0.05	9.6	480.85	
1112871	2	4	1	<1	390	<3	4	<1	31.4	0.092	0.67	<0.05	6.3	468.65	
1112871	1	4	2	<1	260	<3	3	6	37.5	0.054	0.33	<0.05	10.3	288.7	
1113871	1	5	5	<1	320	<3	6	<1	23.6	<0.003	0.27	<0.05	6.7	343.18	
1112871	2	6	1	<1	220	<3	4	<1	26.9	0.022	0.3	<0.05	10.4	268.95	
1112871	1	1	4	<1	330	<3	3	<1	27.3	0.115	0.69	<0.05	8.5	376.31	
1112871	1	3	1	<1	190	<3	2	5	28	0.024	0.45	<0.05	1.9	219.27	
1113871	1	3	7	<1	550	<3	8	<1	39	0.054	0.6	<0.05	15.7	634.02	
1113871	1	2	4	<1	350	<3	2	<1	27.4	0.048	0.48	<0.05	11.3	435.15	
1112871	:	2	4	3	240	<3	3	<1	37	0.045	0.92	<0.05	12.6	431.42	
1112871	1	4	1	<1	340	<3	3	<1	31.1	0.052	0.58	<0.05	10	386.43	
1110872	3	7	2	2	150	<3	4	<1	44.8	0.031	0.57	<0.05	19.9	573.52	
1110871	4	5	1	<1	300	<3	4	22	18.9	0.034	0.25	<0.05	3.5	217.07	
1110871	4	5	4	5	330	<3	4	<1	17.7	0.025	0.22	<0.05	14.3	380.79	
1109871	4	6	8	<1	250	<3	4	<1	12.7	0.128	<0.05	<0.05	3.7	179.62	
1110872	4	6	1	<1	220	<3	2	<1	20.3	0.028	0.39	<0.05	6.2	252.62	
1109871	4	5	8	<1	270	<3	5	11	35.3	<0.003	0.66	<0.05	11.9	326.1	
1110872	3	6	1	<1	160	<3	1	9	13.1		0.41	<0.05	4.7	154.95	
1109871	4	5	1	3	290	<3	5	16	25.1	0.029	0.16	<0.05	12.2	298.13	

Table C.2 Analysis of 10 selected samples for 45 elements. Values shown are element mass on filter in μg .

Test	1112871	1110872	1109871	1113871	1110872	1112871	1110872	1110872	1110872	1110872	1110872
Transect	1	4	4	1	4	1	4	4	4	4	3
Mast	5	5	5	4	5	4	5	5	5	6	7
Height	8	1	2	5	8	4	4	4	2	4	8
Zn	410.76	342.33	338.61	323.96	309.83	289.44	272.86	255.94	228.96	153.83	
Chloride	380	250	280	310	280	260	300	240	170	94	
Fe	109.1	76	129.5	49.1	46.4	82	45.6	49	45.6	29.9	
Na	44.2	46.9	53.8	35.9	43.8	53.7	29	43.1	31	46.4	
Al	28.1	28.6	32.3	20.3	19.9	30.3	18.6	23	14	10.4	
Sulfate	10	8	8	13	22	0	7	10	12	0	
Ca	7.7	4.3	4.8	14.3	9.4	6.5	5.4	11	3.8	15.9	
Pb	9.9	9.7	13.6	4.7	9.6	9.9	6.3	5.5	3.2	3.4	
Si	3.7	2.3	10.1	4.6	2.9	3.1	5.6	4	0	2.4	
Nitrate	3	2	5	3	3	5	2	4	1	2	
Mg	1.148	0.989	1.649	1.527	0.937	1.312	1.282	1.504	1.108	1.253	
Sn	0	3.9	0	1.2	2.1	0	0	1.3	0	2.3	
Bromide	0	0	3	0	0	0	0	0	3	4	
Zr	0.6	0.6	0.8	0.7	0.5	0.7	0.7	0.6	0.6	0.7	
Ba	0.67	1.03	0	0.64	0.92	0.32	0	0.96	0.94	0.78	
B	0	0	3	0	0	0	0	1.2	1	0.9	
Cr	0.6	0.4	0	0	0	0	0.3	0.7	1.6	1.5	
Cu	0.5	0.4	0.3	0	0	0.2	0.2	0.5	0.7	0.5	
Ti	0.2	0.2	0.2	0.1	0.2	0.3	0.1	0.3	0.1	1.5	
P	0	0	0	0	0	0	0	0	0	3	
Cd	0.22	0.19	0.44	0.36	0.17	0.82	0	0.37	0	0.31	
Ag	0	0	0	0	0	0.1	0	1.1	0.4	0.2	
Sb	0.22	0.06	0.14	0.15	0.22	0.41	0.02	0.2	0.07	0	

Table C.2 (continued)

Test	1112871	1110872	1109871	1113871	1110872	1112871	1110872	1110872	1110872	1110872	1110872
Transect	1	4	4	1	4	1	4	4	4	4	3
Mast	5	5	5	4	5	4	5	5	5	6	7
Height	8	1	2	5	8	4	4	4	2	4	8
V	0	0	0.7	0	0	0	0	0.7	0	0	0
Mo	0.2	0	0	0	0.2	0.3	0	0	0.1	0	0.5
Ni	0	0	0	0.6	0.6	0	0	0	0	0	0
Be	0.135	0.092	0	0.126	0.114	0.1	0	0	0.088	0.086	0.072
As	0.107	0.021	0.038	0.061	0.047	0.062	0.014	0.074	0.05	0.048	0.048
Mn	0	0	0.18	0	0.07	0.05	0.11	0	0	0	0
Co	0	0	0	0	0	0	0	0	0	0	0.3
Sr	0.04	0	0	0.08	0	0	0	0.04	0	0	0
Se	0.011	0	0	0	0	0.067	0	0.047	0	0	0
Iodide	0	0	0	0	0	0	0	0	0	0	0
Hg	0	0	0	0	0	0	0	0	0	0	0
Au	0	0	0	0	0	0	0	0	0	0	0
Ce	0	0	0	0	0	0	0	0	0	0	0
K	0	0	0	0	0	0	0	0	0	0	0
La	0	0	0	0	0	0	0	0	0	0	0
Li	0	0	0	0	0	0	0	0	0	0	0
Nd	0	0	0	0	0	0	0	0	0	0	0
Pd	0	0	0	0	0	0	0	0	0	0	0
Pr	0	0	0	0	0	0	0	0	0	0	0
Pt	0	0	0	0	0	0	0	0	0	0	0
Th	0	0	0	0	0	0	0	0	0	0	0
Y	0	0	0	0	0	0	0	0	0	0	0

Appendix D. Vapor Phase Measurements

Table D.1 provides detailed information about the 12 vapor phase samples which were analyzed for tetrachloromethane, tetrachloroethylene, hexachloroethane and hexachlorobenzene.

Table D.1 Detailed data from analysis of HC vapor phase samples for four organic compounds.

Tetrachloromethane

Sample	Test ID	Transect number	Mast number	Sampler height [m]	flow rate [liters/min]	duration [min]	elution time [min]	detector counts	detected mass [µg]	zinc mass [µg]	Ratio to Zinc
1	1110871	4	5.5	1	0.1	36				0.56	
2	1110871	4	6	1	0.1	36	19.24	89207	0.044604	13.35	0.0033
3	1110871	4	6.5	1	0.1	36	19.22	39247	0.019624	1.26	0.0156
4	1110871	4	7	1	0.1	36	18.94	58268	0.029134	0.25	0.1165
5	1110872	4	5.5	1	0.1	47	19.2	89409	0.044705	42.86	0.0010
6	1110872	4	6	1	0.1	47	18.84	59062	0.029531	12.29	0.0024
7	1110872	4	6.5	1	0.1	47	19	115130	0.057565	2.69	0.0214
8	1110872	4	7	1	0.1	47	18.77	331759	0.16588	0.52	0.3190
9	1110872	1	3	1	0.1	47	18.4	67295	0.033648		
10	1112871	1	5	1	0.1	45	17.94	65000	0.0325		
11	1112871	1	6	1	0.1	45	18.53	69682	0.034841	1.92	0.0181
12	1112871	1	5	1	0.1	45	18.25	284587	0.142294		
13	1112871	1	4	1	0.1	45	17.32	227597	0.113799		

Tetrachloroethylene

Sample	Test ID	Transect number	Mast number	Sampler height [m]	flow rate [liters/min]	duration [min]	elution time [min]	detector counts	detected mass [µg]	zinc mass [µg]	Ratio to Zinc
1	1110871	4	5.5	1	0.1	36	20.95	28943	0.014472	0.56	0.0258
2	1110871	4	6	1	0.1	36	22.93	29220	0.01461	13.35	0.0011
3	1110871	4	6.5	1	0.1	36	22.93	18018	0.009009	1.26	0.0072
4	1110871	4	7	1	0.1	36	24.37	89234	0.044617	0.25	0.1785
5	1110872	4	5.5	1	0.1	47	22.93	37310	0.018655	42.86	0.0004
6	1110872	4	6	1	0.1	47	22.49	19472	0.009736	12.29	0.0008
7	1110872	4	6.5	1	0.1	47	22.7	59887	0.029944	2.69	0.0111
8	1110872	4	7	1	0.1	47	22.44	243523	0.121762	0.52	0.2342
9	1110872	1	3	1	0.1	47	22.16	38292	0.019146		
10	1112871	1	5	1	0.1	45	22.3	34106	0.017053		
11	1112871	1	6	1	0.1	45	22.25	34936	0.017468	1.92	0.0200
12	1112871	1	5	1	0.1	45	23.79	21977	0.010989		
13	1112871	1	4	1	0.1	45	22.92	20030	0.010015		

Table D.1 (continued)

Hexachloroethane

Sample	Test ID	Transect number	Mast number	Sampler height [m]	flow rate [liters/min]	duration [min]	elution time [min]	detector counts	detected mass [μg]	zinc mass [μg]	Ratio to Zinc
1	1110871	4	5.5	1	0.1	36	26.98	15189	0.009233	0.56	0.0007
2	1110871	4	6	1	0.1	36	31.12	89480	0.054395	1.26	0.0432
3	1110871	4	6.5	1	0.1	36	27.42	102330	0.062207	0.25	0.2488
4	1110871	4	7	1	0.1	36	26.96	30087	0.01829	42.86	0.0004
5	1110872	4	5.5	1	0.1	47	26.55	21850	0.013283	12.29	0.0011
6	1110872	4	6	1	0.1	47	30.84	101604	0.061765	2.69	0.0230
7	1110872	4	6.5	1	0.1	47	26.5	104973	0.063813	0.52	0.1227
8	1110872	4	7	1	0.1	47	27.02	17234	0.010477		
9	1110872	1	3	1	0.1	45	28.26	19699	0.011975		
10	1112871	1	5	1	0.1	45	30.24	28321	0.017216	1.92	0.0197
11	1112871	1	6	1	0.1	45	27.37	41408	0.025172		
12	1112871	1	5	1	0.1	45	27.63	29643	0.01802		
13	1112871	1	4	1	0.1	45					

Hexachlorobenzene

Sample	Test ID	Transect number	Mast number	Sampler height [m]	flow rate [liters/min]	duration [min]	elution time [min]	detector counts	detected mass [μg]	zinc mass [μg]	Ratio to Zinc
1	1110871	4	5.5	1	0.1	36	45.26	450300	0.180989	0.56	0.3232
2	1110871	4	6	1	0.1	36	45.44	25326	0.010179	13.35	0.0008
3	1110871	4	6.5	1	0.1	36	42.3	197576	0.079412	1.26	0.0630
4	1110871	4	7	1	0.1	36	42.05	314402	0.126367	0.25	0.5055
5	1110872	4	5.5	1	0.1	47	44.35	86801	0.034888	42.86	0.0008
6	1110872	4	6	1	0.1	47	44.06	322951	0.129803	12.29	0.0106
7	1110872	4	6.5	1	0.1	47	45.16	242179	0.097339	2.69	0.0362
8	1110872	4	7	1	0.1	47	44.02	426298	0.171342	0.52	0.3295
9	1110872	1	3	1	0.1	47	47.18	265537	0.106727		
10	1112871	1	5	1	0.1	45	50.41	16978	0.006824		
11	1112871	1	6	1	0.1	45	45.93	113969	0.045807	1.92	0.0523
12	1112871	1	5	1	0.1	45	42.34	153883	0.06185		
13	1112871	1	4	1	0.1	45	44.28	887600	0.356752		

Appendix E. Concentration Data

This appendix summarizes the concentration data acquired in the five HC smoke trials conducted as part of the Atterbury-87 field study. Tables E.1 through E.5 list the data for Tests 1109871, 1110871, 1110872, 1112871 and 1113871, respectively. Each value represents an average over all four measurement heights. The data have been corrected for the effect of filter loading using the procedure described in the text.

Table E.1 Concentration data for Test 1109871.

Test: 1109871

Duration = 25 min.

Flowrate = 18.1 lpm

Total Mass Released = 222.1 kg

Average Release Rate = 148.1 g/s

Transect	Mast	x [m]	y [m]	Distance to center of transect [m]	Distance to source [m]	Concentration [mg/m ³]
1	1	-11.7	80.9	-65.1	481.2	0.0033
1	2	-1.7	70.6	-50.7	483.9	0.0050
1	3	8.6	60.2	-36.1	486.9	0.0096
1	4	18.8	50.1	-21.7	490.2	0.0143
1	5	28.6	39.8	-7.3	494.0	0.0177
1	6	39.4	29.1	7.7	498.4	0.0383
1	7	49.4	19.3	21.7	502.7	0.0877
1	8	59.3	9.2	35.8	507.5	0.2493
1	9	69.7	-1.4	50.7	513.0	0.4036
1	10	79.9	-11.5	65.0	518.5	0.3897
2	1	-41.5	188.7	-161.9	420.5	0
2	2	-21.3	136.7	-132.1	421.3	0
2	3	-2.3	146.1	-104.1	424.0	0
2	4	18.0	124.3	-74.3	428.6	0.0045
2	5	38.7	102.1	-44.0	435.4	0.0077
2	6	59.1	80.0	-13.9	444.2	0.0393
2	7	79.0	58.3	15.6	454.7	0.2517
2	8	98.8	36.8	44.8	466.7	0.5281
2	9	118.2	15.6	73.6	479.9	0.2679
2	10	138.0	-5.8	102.7	494.6	0.7805
2	11	157.9	-27.2	132.0	510.6	0.3053
2	12	178.0	-49.0	161.6	527.9	0.4823
3	1	0.3	348.2	-238.4	296.5	0.0004
3	2	31.3	317.3	-194.7	284.1	0.0004
3	3	61.5	287.0	-151.9	278.1	0.0007
3	4	91.8	256.7	-109.1	278.7	0.0032
3	5	122.6	225.9	-65.5	286.0	0.0651
3	6	153.6	194.9	-21.7	299.5	0.2900
3	7	184.0	164.5	21.3	318.2	0.4986
3	8	215.1	133.4	65.3	341.9	0.4363
3	9	246.4	102.1	109.6	369.5	0.3674
3	10	276.7	71.8	152.4	399.1	0.3076
3	11	306.7	41.9	194.8	430.5	0.0254
3	12	337.1	11.4	237.9	464.2	0.0003
4	1	74.7	543.6	-312.3	208.7	0
4	2	113.9	507.6	-259.0	160.7	0
4	3	154.5	466.4	-201.2	115.9	0
4	4	194.3	427.3	-145.4	87.6	0
4	5	235.1	388.3	-89.0	89.7	86.716
4	6	275.5	349.3	-32.9	121.6	5.8605
4	7	315.5	308.7	24.9	168.6	0.0139
4	8	357.7	267.3	83.3	221.5	0
4	9	398.8	225.9	141.6	276.6	0.0001
4	10	440.0	184.1	200.3	333.2	0
4	11	485.1	137.4	265.5	396.8	0
4	12	526.1	95.2	324.2	454.5	0

Table E.2 Concentration data for Test 1110871.

Test: 1110871
 Duration = 36.5 min.
 Flowrate = 18.1 lpm

Total Mass Released = 229.3 kg
 Average Release Rate = 104.7 g/s

Transect	Mast	x [m]	y [m]	Distance to center of transect [m]	Distance to source [m]	Concentration [mg/m ³]
1	1	-11.7	80.9	-65.1	481.2	0.4626
1	2	-1.7	70.6	-50.7	483.9	0.4125
1	3	8.6	60.2	-36.1	486.9	0.5418
1	4	18.8	50.1	-21.7	490.2	0.5488
1	5	28.8	39.8	-7.3	494.0	0.3268
1	6	39.4	29.1	7.7	498.4	0.8934
1	7	49.4	19.3	21.7	502.7	0.5165
1	8	59.3	9.2	35.8	507.5	0.7108
1	9	69.7	-1.4	50.7	513.0	0.2447
1	10	79.9	-11.5	65.0	518.5	0.3267
2	1	-41.5	188.7	-161.9	420.5	0.1033
2	2	-21.3	166.7	-132.1	421.3	0.2205
2	3	-2.3	146.1	-104.1	424.0	0.2624
2	4	18.0	124.3	-74.3	428.6	0.4405
2	5	38.7	102.1	-44.0	435.4	0.2370
2	6	59.1	80.0	-13.9	444.2	0.4015
2	7	79.0	58.3	15.6	454.7	0.3513
2	8	98.8	36.8	44.8	466.7	0.2730
2	9	118.2	15.6	73.6	479.9	0.6155
2	10	138.0	-5.8	102.7	494.6	0.1661
2	11	157.9	-27.2	132.0	510.6	0.0734
2	12	178.0	-49.0	161.6	527.9	0.0363
3	1	0.3	348.2	-238.4	296.5	0
3	2	31.3	317.3	-194.7	284.1	0
3	3	61.5	287.0	-151.9	278.1	0.1380
3	4	91.8	256.7	-109.1	278.7	0.2301
3	5	122.6	225.9	-65.5	286.0	0.2883
3	6	153.6	194.9	-21.7	299.5	0.2638
3	7	184.0	164.5	21.3	318.2	0.1972
3	8	215.1	133.4	65.3	341.9	0.1199
3	9	246.4	102.1	109.6	369.5	0.0069
3	10	276.7	71.8	152.4	399.1	0.0007
3	11	306.7	41.9	194.8	430.5	0
3	12	337.1	11.4	237.9	464.2	0.0002
4	1	74.7	543.6	-312.3	208.7	0
4	2	113.9	507.6	-259.0	160.7	0
4	3	154.5	466.4	-201.2	115.9	0.0003
4	4	194.3	427.3	-145.4	87.6	0.0042
4	5	235.1	388.3	-89.0	89.7	13.243
4	6	275.5	349.3	-32.9	121.6	0.2163
4	7	316.5	308.7	24.9	168.6	0
4	8	357.7	267.3	83.3	221.5	0
4	9	398.8	225.9	141.6	276.6	0
4	10	440.0	184.1	200.3	333.2	0
4	11	485.5	137.4	265.5	396.8	0
4	12	526.3	95.2	324.2	454.5	0

Table E.3 Concentration data for Test 1110872.

Test: 1110872
 Duration = 47.3 min.
 Flowrate = 18.1 lpm

Total Mass Released = 219.5 kg
 Average Release Rate = 77.3 g/s

Transect	Mast	x [m]	y [m]	Distance to center of transect [m]	Distance to source [m]	Concentration [mg/m ³]
1	1	-11.7	80.9	-65.1	481.2	0.0125
1	2	-1.7	70.6	-50.7	483.9	0.0300
1	3	8.6	60.2	-36.1	486.9	0.0828
1	4	18.8	50.1	-21.7	490.2	0.1417
1	5	28.8	39.8	-7.3	494.0	0.3052
1	6	39.4	29.1	7.7	498.4	0.5935
1	7	49.4	19.3	21.7	502.7	0.2636
1	8	59.3	9.2	35.8	507.5	0.3087
1	9	69.7	-1.4	50.7	513.0	0.2788
1	10	79.9	-11.5	65.0	518.5	0.1781
2	1	-41.5	188.7	-161.9	420.5	0
2	2	-21.3	166.7	-132.1	421.3	0
2	3	-2.3	146.1	-104.1	424.0	0.0006
2	4	18.0	124.3	-74.3	428.6	0.0159
2	5	38.7	102.1	-44.0	435.4	0.0777
2	6	59.1	80.0	-13.9	444.2	0.1911
2	7	79.0	58.3	15.6	454.7	0.1873
2	8	98.8	36.8	44.8	466.7	0.1773
2	9	118.2	15.6	73.6	479.9	0.1537
2	10	138.0	-5.8	102.7	494.6	0.1391
2	11	157.9	-27.2	132.0	510.6	0.1474
2	12	178.0	-49.0	161.6	527.9	0.1643
3	1	0.3	348.2	-238.4	296.5	0
3	2	31.3	317.3	-194.7	284.1	0
3	3	61.5	287.0	-151.9	278.1	0
3	4	91.8	256.7	-109.1	278.7	0.0149
3	5	122.6	225.9	-65.5	286.0	0.8783
3	6	153.6	194.9	-21.7	299.5	0.2597
3	7	184.0	164.5	21.3	318.2	0.3438
3	8	215.1	133.4	65.3	341.9	0.1816
3	9	246.4	102.1	109.6	369.5	0.1700
3	10	276.7	71.8	152.4	399.1	0.1478
3	11	306.7	41.9	194.8	430.5	0.0992
3	12	337.1	11.4	237.9	464.2	0.019
4	1	74.7	543.6	-312.3	208.7	0
4	2	113.9	507.6	-259.0	160.7	0
4	3	154.5	466.4	-201.2	115.9	0
4	4	194.3	427.3	-145.4	87.6	0
4	5	235.1	388.3	-89.0	89.7	8.9107
4	6	275.5	349.3	-32.9	121.6	1.4467
4	7	316.5	308.7	24.9	168.6	0.0145
4	8	357.7	267.3	83.3	221.5	0
4	9	398.8	225.9	141.6	276.6	0
4	10	440.0	184.1	200.3	333.2	0
4	11	485.5	137.4	265.5	396.8	0
4	12	526.3	95.2	324.2	454.5	0

Table E.4 Concentration data for Test 1112871.

Test: 1112871
Duration = 45.7 min.
Flowrate = 18.1 lpm

Total Mass Released = 218.5 kg
Average Release Rate = 79.7 g/s

Transect	Mast	x [m]	y [m]	Distance to center of transect [m]	Distance to source [m]	Concentration [mg/m ³]
1	1	-11.7	80.9	-65.1	60.5	65.669
1	2	-1.7	70.6	-50.7	53.2	72.740
1	3	8.6	60.2	-36.1	49.1	114.49
1	4	18.8	50.1	-21.7	49.3	86.936
1	5	28.8	39.8	-7.3	53.3	49.538
1	6	39.4	29.1	7.7	61.0	0.3395
1	7	49.4	19.3	21.7	70.5	0.0279
1	8	59.3	9.2	35.8	81.2	0.0006
1	9	69.7	-1.4	50.7	93.6	0
1	10	79.9	-11.5	65.0	106.1	0
2	1	-41.5	188.7	-161.9	168.8	0
2	2	-21.3	166.7	-132.1	145.6	0.0334
2	3	-2.3	146.1	-104.1	126.4	0.8347
2	4	18.0	124.3	-74.3	110.3	13.485
2	5	38.7	102.1	-44.0	100.7	25.318
2	6	59.1	80.0	-13.9	99.5	11.480
2	7	79.0	58.3	15.6	106.8	0.8537
2	8	98.8	36.8	44.8	120.9	0.0171
2	9	118.2	15.6	73.6	139.4	0
2	10	138.0	-5.8	102.7	161.4	0
2	11	157.9	-27.2	132.0	185.5	0.0003
2	12	178.0	-49.0	161.6	211.1	0
3	1	0.3	348.2	-238.4	327.8	0.0008
3	2	31.3	317.3	-194.7	300.7	0.0061
3	3	61.5	287.0	-151.9	278.5	0.1791
3	4	91.8	256.7	-109.1	261.3	0.7483
3	5	122.6	225.9	-65.5	250.2	0.9302
3	6	153.8	194.9	-21.7	246.5	0.8486
3	7	184.0	164.5	21.3	250.3	0.3742
3	8	215.1	133.4	65.3	261.6	0.0697
3	9	246.4	102.1	109.6	279.5	0.0012
3	10	276.7	71.8	152.4	302.1	0
3	11	306.7	41.9	194.8	328.4	0
3	12	337.1	11.4	237.9	358.4	0
4	1	74.7	543.6	-312.3	521.2	0
4	2	113.9	507.6	-259.0	504.9	0.0042
4	3	154.5	466.4	-201.2	478.7	0.0029
4	4	194.3	427.3	-145.4	459.8	0.1634
4	5	235.1	388.3	-89.0	447.7	0.3225
4	6	275.5	349.3	-32.9	442.3	0.1948
4	7	316.5	308.7	24.9	443.4	0.1027
4	8	357.7	267.3	83.3	451.8	0.0187
4	9	398.8	225.9	141.6	467.2	0.0101
4	10	440.0	184.1	200.3	489.0	0
4	11	485.5	137.4	265.5	519.8	0
4	12	526.3	95.2	324.2	552.4	0

Table E.5 Concentration data for Test 1113871.

Test: 1113871

Duration = 43 min.

Flowrate = 10.8 lpm (Transect 1)

Flowrate = 18.1 lpm (Transects 2, 3 and 4)

Total Mass Released = 202.0 kg

Average Release Rate = 78.3 g/s

Transect	Mast	x [m]	y [m]	Distance to center of transect [m]	Distance to source [m]	Concentration [mg/m ³]
1	1	-11.7	80.9	-65.1	60.5	1.5655
1	2	-1.7	70.6	-50.7	53.2	86.238
1	3	8.6	60.2	-36.1	49.1	79.054
1	4	18.8	50.1	-21.7	49.3	33.220
1	5	28.8	39.8	-7.3	53.3	17.799
1	6	39.4	29.1	7.7	61.0	0.5096
1	7	49.4	19.3	21.7	70.5	1.8328
1	8	59.3	9.2	35.8	81.2	0.8024
1	9	69.7	-1.4	50.7	93.6	0.2130
1	10	79.9	-11.5	65.0	106.1	0.1320
2	1	-41.5	188.7	-161.9	168.8	0
2	2	-21.3	166.7	-132.1	145.6	0.0005
2	3	-2.3	146.1	-104.1	126.4	0.0126
2	4	18.0	124.3	-74.3	110.3	0.6207
2	5	38.7	102.1	-44.0	100.7	0.2838
2	6	59.1	80.0	-13.9	99.5	28.572
2	7	79.0	58.3	15.6	106.8	10.444
2	8	98.8	36.8	44.8	120.9	1.6329
2	9	118.2	15.6	73.6	139.4	0.1094
2	10	138.0	-5.8	102.7	161.4	0.0693
2	11	157.9	-27.2	132.0	185.5	0.0104
2	12	178.0	-49.0	161.6	211.1	0.0003
3	1	0.3	348.2	-238.4	327.8	0.0002
3	2	31.3	317.3	-194.7	300.7	0.0002
3	3	61.5	287.0	-151.9	278.5	0.0006
3	4	91.8	256.7	-109.1	261.3	0.0801
3	5	122.6	225.9	-65.5	250.2	0.9127
3	6	153.6	194.9	-21.7	246.5	1.5120
3	7	184.0	164.5	21.3	250.3	7.2382
3	8	215.1	133.4	65.3	261.6	1.1058
3	9	246.4	102.1	109.6	279.5	0.1531
3	10	276.7	71.8	152.4	302.1	0.0248
3	11	306.7	41.9	194.3	328.4	0.0141
3	12	337.1	11.4	237.9	358.4	0.0001
4	1	74.7	543.6	-312.3	531.2	0
4	2	113.9	507.6	-259.0	504.9	0.0008
4	3	154.5	466.4	-201.2	478.7	0
4	4	194.3	427.3	-145.4	459.8	0.0009
4	5	235.1	388.3	-89.0	447.7	0.0854
4	6	275.5	349.3	-32.9	442.3	0.6863
4	7	316.5	308.7	24.9	443.4	0.7027
4	8	357.7	267.3	83.3	451.8	0.3870
4	9	398.8	225.9	141.6	467.2	0.1658
4	10	440.0	184.1	200.3	489.0	0.0494
4	11	485.5	137.4	265.5	519.8	0.0084
4	12	526.3	95.2	324.2	552.4	0.0019

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